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OF THE NASA LEWIS RESEARCH CENTER, 1989]  
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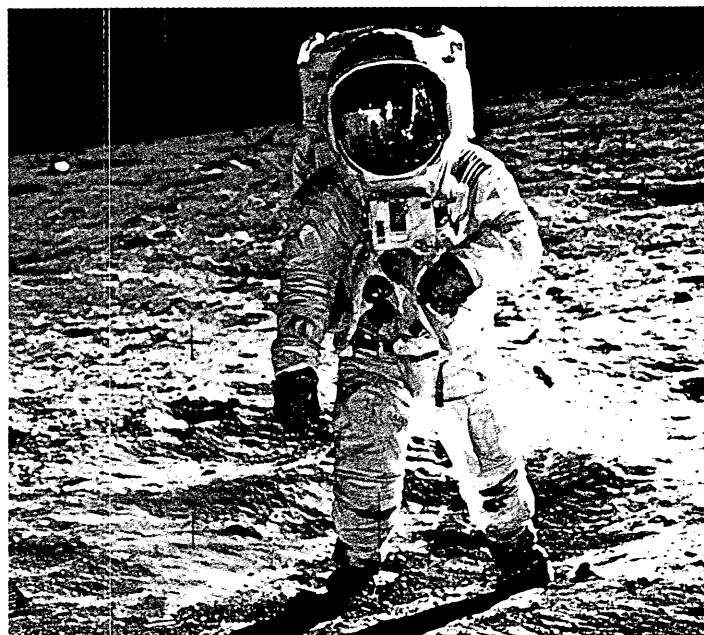
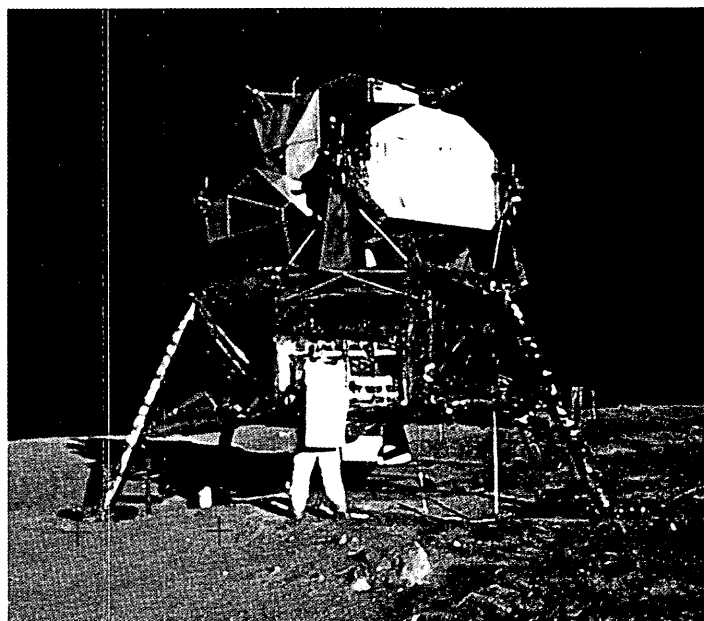
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## Commemorative Issue

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**Lewis Contributions in  
Liquid-Hydrogen Propulsion  
Made the Dream a Reality**





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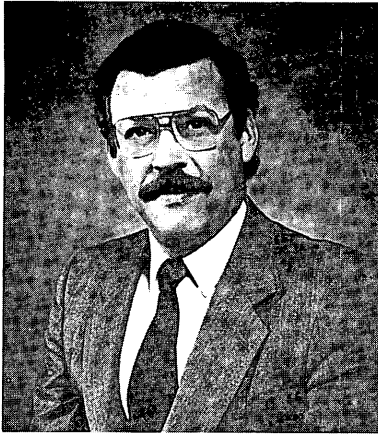
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Cleveland, Ohio 44135

**TM-102296**

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# Introduction

The 1989 Annual Report is dedicated to the 20th Anniversary of the Apollo 11 landing on the Moon. The inside of the cover depicts the major contributions to the Apollo program made by the Lewis Research Center.

The report is organized topically to match the Center's Strategic Plan. Short articles have been prepared to summarize the progress made in the various technical areas and also to portray the technical and administrative support associated with the technology program. Detailed information about each project has been omitted in the interest of brevity. If additional information is desired, the reader is encouraged to contact the authors identified in the articles, who will provide references to published reports, journal articles, and other special publications.

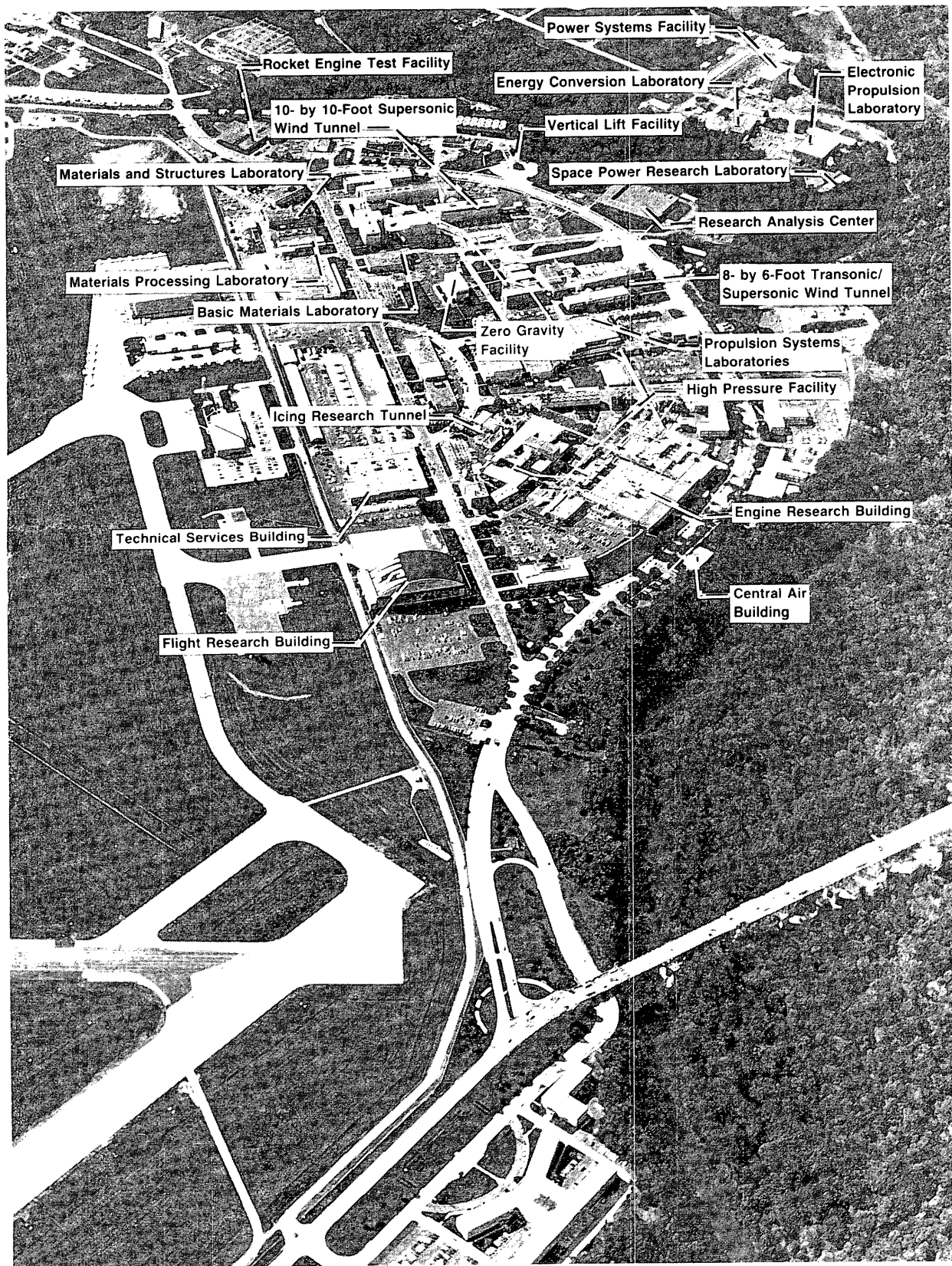
The principal purpose of this report is to give a brief but comprehensive review of the technical accomplishments of the Center during this past year. It is a testimony to the dedication and competence of all the employees, civil servants and contractors, who make up the staff. The report also illustrates the vital relationships the Center has with NASA Headquarters, other NASA centers, the aerospace industry, universities, and other Government laboratories. The Lewis Research Center is pleased to have the opportunity to serve the Nation in performing needed research and technology development in support of NASA's mission.

A handwritten signature in black ink, reading "John M. Klineberg". The signature is stylized, with a large, sweeping "J" and "K".

John M. Klineberg  
Director

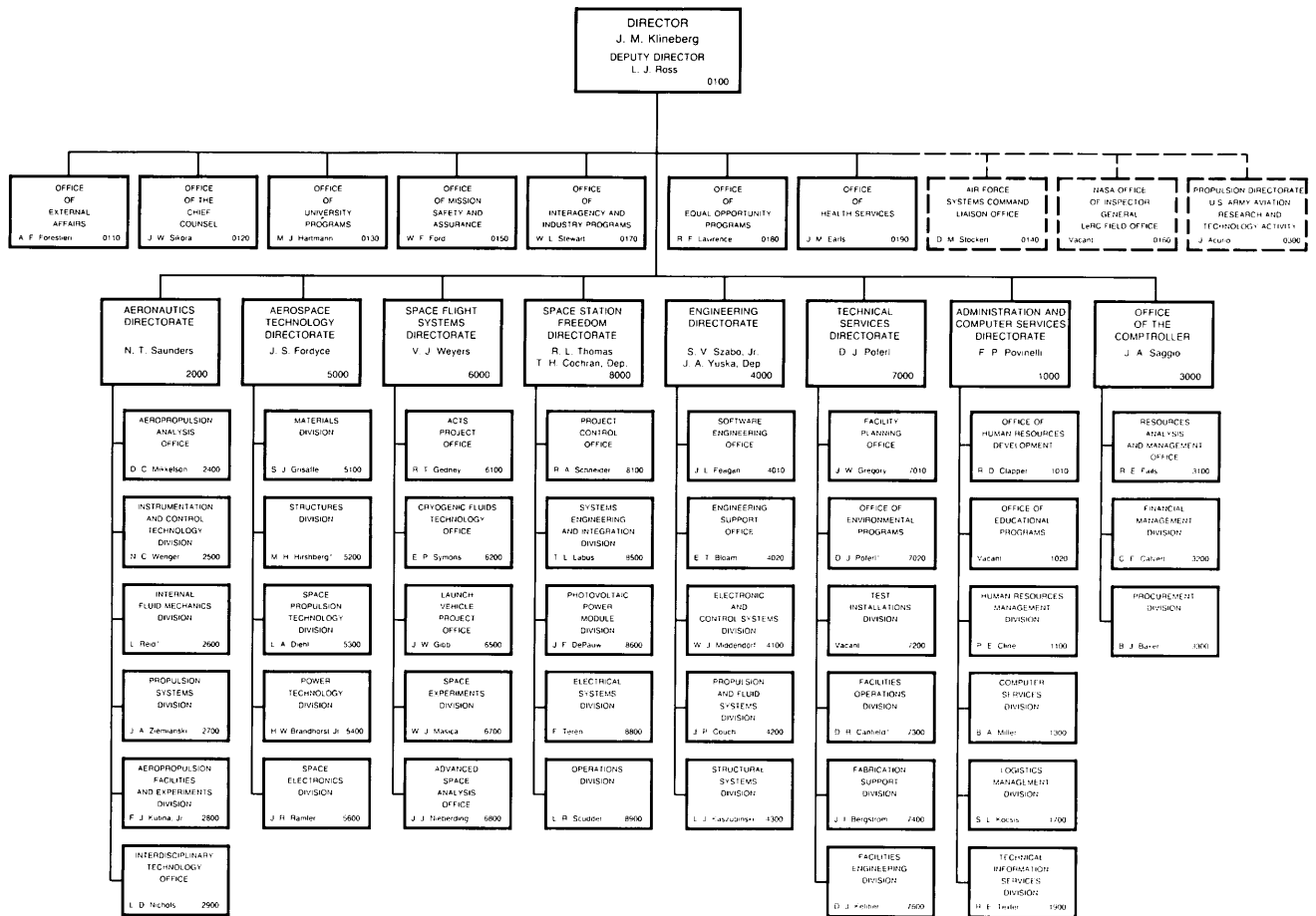
Inquiries regarding this report can be addressed to the Technology Assessment Office, Mail Stop 3-17. The telephone number is (216) 433-5382 or FTS 297-5382.

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Lewis Research Center, Cleveland, Ohio

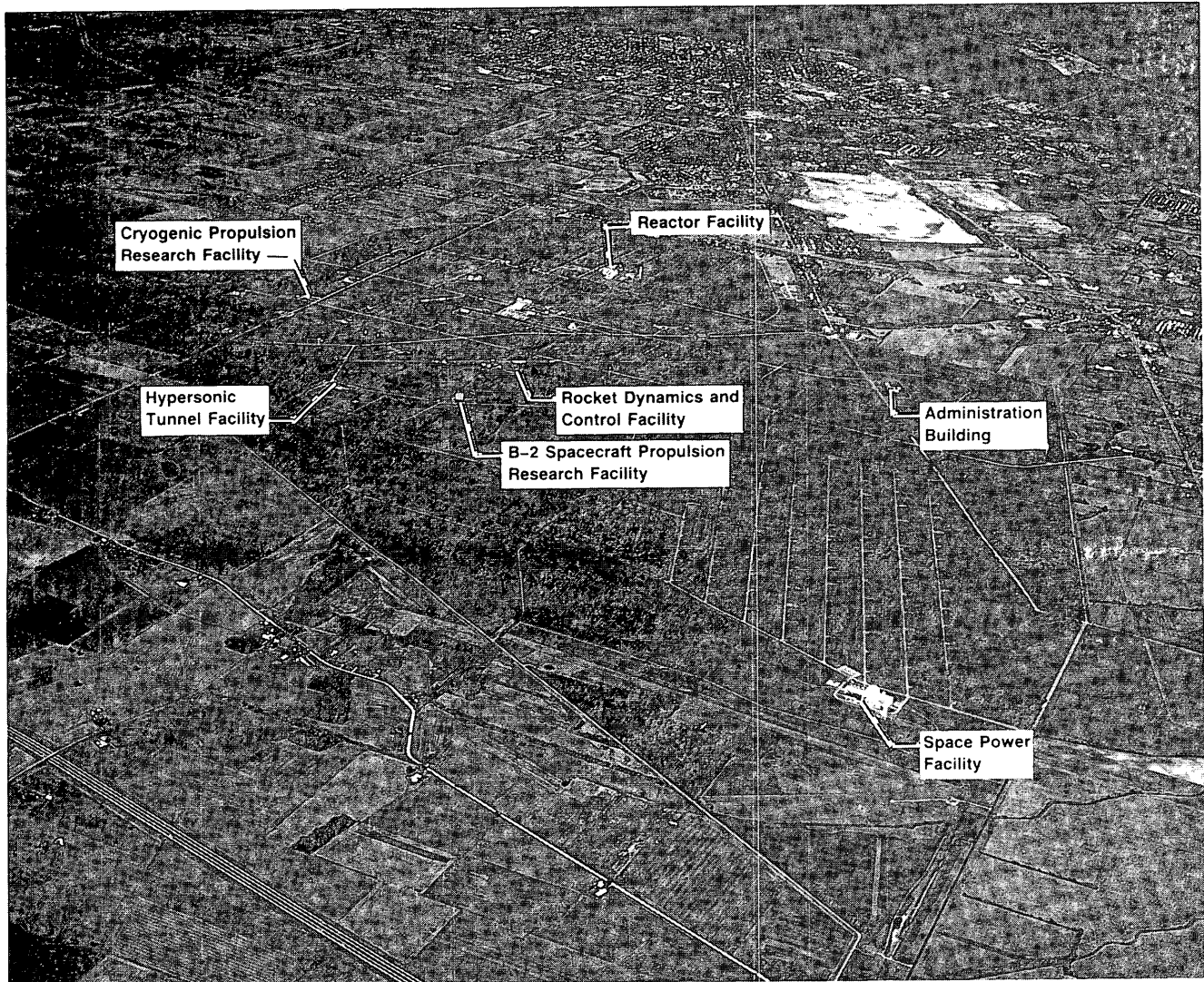
# NASA LEWIS RESEARCH CENTER



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*Plum Brook Station, Sandusky, Ohio*

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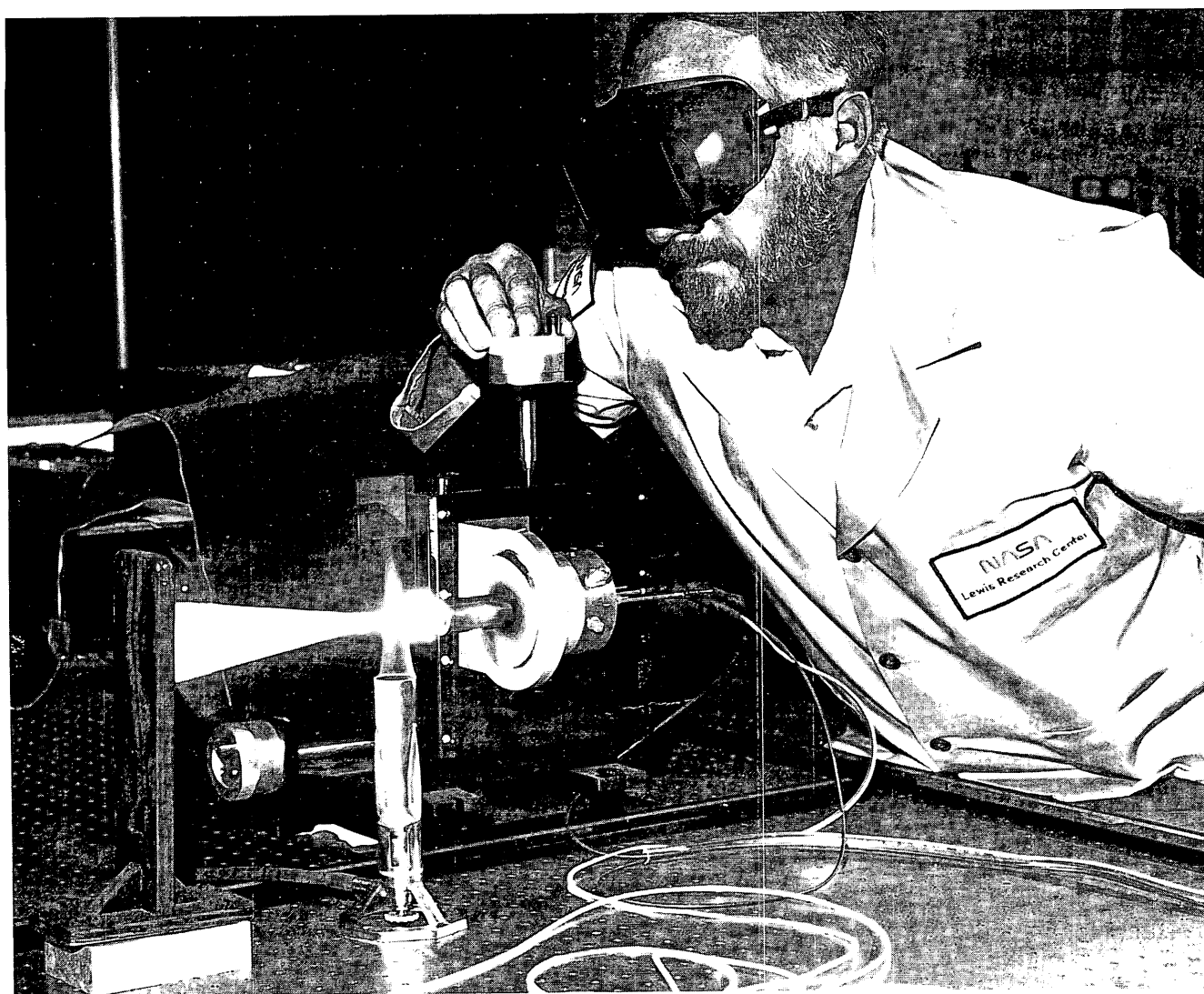
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# Basic Disciplines

## Strategic Objectives

- To enhance Lewis' excellence in the basic and applied technical disciplines essential to our mission in aeropropulsion, space propulsion, space power, and space science and applications. These disciplines are materials science and technology, structural mechanics, life prediction, internal computational fluid mechanics, heat transfer, instruments and controls, and space electronics.
- To strengthen vertical integration of the various basic discipline areas with the major Lewis technology and project thrusts so that a continuum from fundamental to interdisciplinary applied work will be achieved.
- To gradually change the space electronics activities from primary emphasis on commercial communications needs to meeting future NASA needs, and to broaden this area to include basic and applied capabilities in fault-tolerant system autonomy and expert systems in support of space power and space propulsion thrusts.



# Program

## Small Business Innovation Research

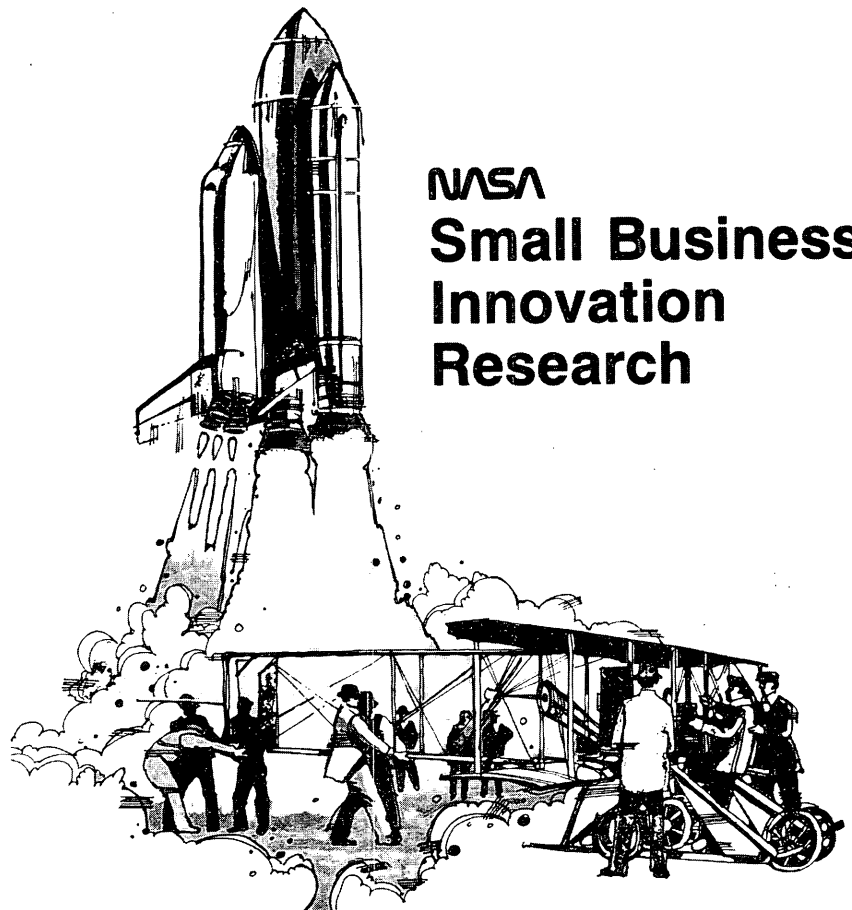
The Small Business Innovation Research (SBIR) Program is a congressionally mandated program aimed at the commercialization of innovative concepts by small business. These innovations are in general areas of research based on the needs of the U.S. Government. NASA is required to allocate 1.25 percent of its annual R&D budget appropriation to its SBIR program. Lewis' share of the NASA SBIR program was \$9.4 million in 1988.

In the spring of each year small businesses are invited to submit proposals addressed to specific technical areas. Lewis welcomes participation in several areas, including aeronautical propulsion and power, materials and structures, space power systems, space propulsion systems, satellite and space communications, and microgravity science. Proposals submitted to these and other technical areas are in competition for 6-month phase I contracts of up to \$50,000. For the 1988 SBIR cycle, Lewis reviewed 536 proposals and made 34 awards. Successful phase I contractors are eligible to compete for a phase II award, which is not to exceed \$500,000 and 24 months. Approximately half of the successful phase I contractors will receive phase II awards. Phase III of the program, which is not funded by SBIR, is primarily for private sector investment to complete any development needed to commercialize the innovation.

Lewis has found SBIR a productive way to involve small business in the Nation's aerospace industry.

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# Research & Technology

## Materials

### Chemical Vapor Deposition Modeling

Developing sophisticated materials in response to more stringent performance requirements necessitates a deeper understanding of the chemical vapor deposition (CVD) processes involved in their fabrication.

Although CVD is routinely used, the success and improvement of its applications depend strongly on correctly characterizing the complex physiochemical interactions in the process. Therefore, the essential role of modeling for an enhanced level of understanding is better appreciated today.

Computational fluid dynamic codes, such as FLUENT and FIDAP, are currently being employed at NASA Lewis to design and optimally operate the reactors in our in-house CVD facility. In support of the NASA HITEMP Program these reactors provide the capability to coat or grow fibers used for reinforcing structural composites, to coat bulk materials for protection against environmental attack, and to infiltrate porous preforms to make and densify ceramic composites.

For code verification purposes FLUENT/CVD has been adopted to simulate an experimental three-dimensional CVD reactor used for obtaining two-dimensional deposition rate data. The code is capable of incorporating gas-phase and surface chemistry with finite reaction rates and is currently being extended to include Soret diffusion. Our calculations have provided invaluable insights about the effects of gravitationally induced, buoyancy-driven convection and the resulting complicated three-dimensional transport

phenomena. Preliminary predictions (without Soret diffusion) of two-dimensional silicon deposition rate profiles from silane dissociation compare favorably with experimental results.

Another computational package, FIDAP, was adapted to simulate a CVD reactor used for growing and coating fibers. The temperature fields inside, within the quartz reactor wall, and outside the reactor were calculated by simultaneously considering a fully coupled conjugate heat transfer problem including radiation. It was demonstrated that owing to radiation, temperature fields inside the reactor can be significant, with important consequences for deposition rates and uniformity. The analysis determined the effects of mixed convection phenomena for different reactor configurations with respect to gravity vector, flow rates, carrier gases, etc. Calculated equilibrium reactor wall temperatures under a range of gas-phase transport and first-order surface kinetics were parametrically varied. In synergism with complementary experimental work, future efforts will be directed toward establishing the relationship between controllable CVD parameters and the resulting microstructures in order to obtain the desired material property.

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Gokoglu, S.A., et al.: Convection and Chemistry Effects in CVD—A 3-D Analysis for Silicon Deposition, Proc. Seventh European Conf. on Chemical Vapor Deposition, les Editions de Physique, M. Ducarroir, et al., eds., 1989, C5-17; also NASA TM-102001, 1989.

Gokoglu, S.A., et al.: Prediction of 2-D Convection Effects and Deposition Rates in a Reactor Configured for CVD on Single Fibers. Proceedings of 1989 ASME Winter Annual Meeting, Fluids Engineering Division, Forum on Transport Phenomena in Manufacturing, Dec. 10-15, 1989.

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**Headquarters program office:** OAST

## Silicon Carbide Matrices for High-Temperature Composites

For advanced gas turbine engines and advanced supersonic aircraft, where properties such as strength, toughness, and oxidation resistance must exceed those of today's high-temperature alloys, ceramic-fiber-reinforced ceramic matrix composites are a viable material. Many ceramic composite systems that use oxide and nonoxide fibers and matrices have been proposed and studied. Research is under way at NASA Lewis to produce a silicon carbide matrix by converting a microporous carbon preform.

Because of the large exothermic reaction between liquid silicon, used to convert the microporous carbon preforms, and the preforms, the rate at which silicon is introduced into the preform must be kept low to prevent damaging high temperatures. Of the conversion methods studied at NASA Lewis, two have produced controlled siliconization of the preforms: chemical vapor deposition (CVD) and chemical vapor infiltration (CVI). In CVD, silicon from a mixture of silicon tetrachloride vapor and hydrogen gas is deposited on the surface of a heated preform. The deposited silicon diffuses into the interior of the preform. This method can be used to convert thin sections. In CVI, an extension of this method just now starting to be studied at Lewis, a low-pressure mixture of silicon tetrachloride vapor and hydrogen gas will be used to deposit silicon throughout the microporous preform. This method should be able to convert thicker sections than the CVD method.

In another method being studied at Lewis, liquid silicon is conducted

through a carbon felt wick to control the rate of silicon flow into the heated microporous carbon preform, converting the carbon to silicon carbide. In this method the remaining pores are mostly filled with silicon. In the CVD method and possibly the CVI method the remaining pores are mostly free of silicon.

Studies are in progress to incorporate Textron SCS-6 and Nicalon into the microporous carbon preforms. Both of these reinforced preforms have been converted to silicon carbide by the carbon felt wick method. Mechanical property testing of the SCS-6 reinforced composites is presently under way.

The microporous carbon preforms are made by starting with a liquid polymer mixture that is polymerized at 60 °C and pyrolyzed to 1000 °C. Fiber or whisker reinforcements can be added to the liquid polymer mixture to produce reinforced silicon carbide composites. The liquid polymer starting point makes it easy to produce complex shapes.

### Bibliography

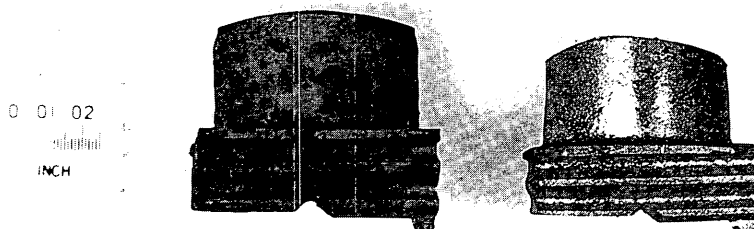
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Hucke, E.E.: Methods of Producing Carbonaceous Bodies and the Products Thereof. United States Patent No. 3,859,421, Jan. 7, 1975.

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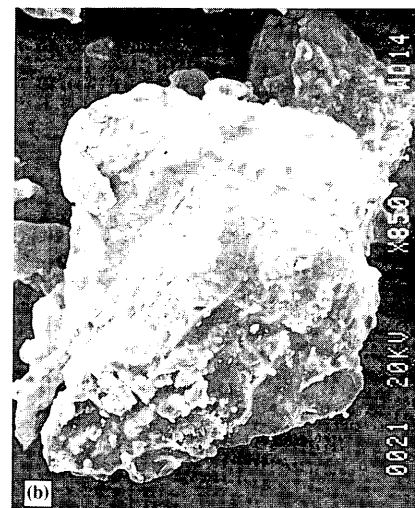
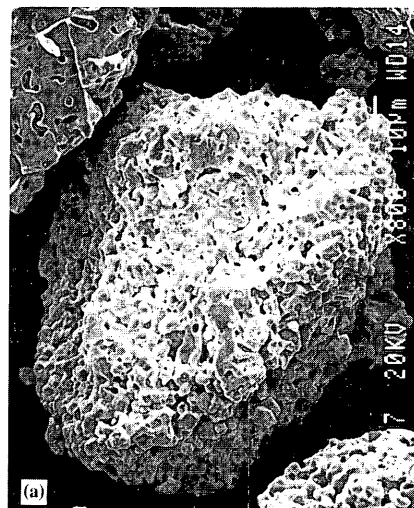
*Unreinforced demonstration blade after pyrolizing and similar blade after conversion to silicon carbide by carbon felt wick method*

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### Composite $\text{ZrO}_2$ -Glass Thermal Barrier Coating

Ceramic thermal barrier coatings (TBC's) and their potential benefits for high-temperature gas turbine components have been the subject of numerous investigations. The state of the art of producing zirconia TBC's has reached a certain level that is not fully satisfactory. Only marginal improvements can be made in the quality of TBC's by optimizing their current fabrication procedures. It has been established that the main causes of TBC failure (cracking and spallation) are oxidation of the bond coat and thermal fatigue of zirconia. The zirconia coating contains 6 to 9 percent porosity, which helps to alleviate the problem of thermal fatigue but opens paths for oxygen or other corrosive species to reach the bond coat. The concept described here is aimed at improving the performance and reliability of zirconia TBC's by filling the pores and cracks in the zirconia with a glass. The role of the glass is to reduce the ingress of oxygen and other corrosive species to the bond coat and to enhance the thermal cycle durability of the zirconia layer through self-healing at use temperature. The glass should be compatible with yttria-stabilized zirconia, have a thermal expansion coefficient equal to or smaller than that of zirconia, be viscous at use temperature ( $1200^\circ\text{C}$ ), and wet zirconia.

On the basis of a literature search, 25 compositions in  $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$  and  $\text{CaO-Al}_2\text{N}_3\text{-SiO}_2$  systems were prepared and tested for compatibility with yttria-stabilized zirconia at  $1300^\circ\text{C}$  for 175 hours. These tests and other considerations such as thermal expansion, melting points, and viscosity led to the selection of a eutectic composition containing



*Morphology of zirconia particles: (a) as received, (b) glass coated*

23 wt %  $\text{CaO}$ , 15 wt %  $\text{Al}_2\text{O}_3$ , and 62 wt %  $\text{SiO}_2$ . The glass was prepared by mixing the appropriate amounts of  $\text{CaCO}_3$ ,  $\text{Al}_2\text{O}_3\cdot 3\text{H}_2\text{O}$ , and  $\text{SiO}_2$  and reacting at  $1500^\circ\text{C}$ . The glass was comminuted in a roller crusher. Mixtures of zirconia and glass representing volume ratios of 9:1 and 4:1 were prepared by mechanical blending of powders, heat treated at  $1400^\circ\text{C}$  for 20 hours, and comminuted. Such composite powders sprayed on cylindrical bars and reference samples coated only with zirconia will be tested at  $1200^\circ\text{C}$  in a Mach 0.3 burner rig to determine if composite  $\text{ZrO}_2$ -glass TBC's can indeed lead to longer life.

A simpler alternative method of producing zirconia-glass powders was investigated. It is based on the preparation of glass by the sol-gel technique. The method ensures an intimate and uniform distribution of glass in the resulting microstructures. Coatings produced by this method will also be tested to determine the advantages of the more uniform microstructures.

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## Chemical Stability of Ceramic Materials in Hydrogen Atmospheres

Structural ceramics and ceramic composites are prime candidates for use in the hot section of advanced high-temperature propulsion systems for future aerospace applications such as the Stirling engine, advanced Earth-to-orbit propulsion systems, and the national aerospace plane (NASP). Hydrogen is being considered as a fuel for many of these advanced propulsion systems. Their hot-section environments are therefore likely to range from pure hydrogen to hydrogen plus moisture. The potential use of ceramic components in these advanced propulsion systems would thus be dictated by their chemical stability in hydrogen-containing environments at elevated temperatures. Thermochemical analysis is useful in screening materials.

Equilibrium calculations based on the principle of minimization of the system's total free energy were performed to examine the chemical stability of different ceramic materials in hydrogen-containing environments as a function of temperature, total system pressure, and moisture content in the atmosphere. The ceramic materials considered in this study were SiC, Si<sub>3</sub>N<sub>4</sub>, Al<sub>2</sub>O<sub>3</sub>, Mullite, BeO, ZrO<sub>2</sub>, CaO, MgO, Y<sub>2</sub>O<sub>3</sub>, TiC, TiB<sub>2</sub>, HfC, and ZrC.

One of the important objectives of thermodynamic calculations is to estimate an upper temperature limit for effective use of the ceramic materials in a given environment. Gaseous products are formed from the reaction of ceramic materials in hydrogen-containing environments.

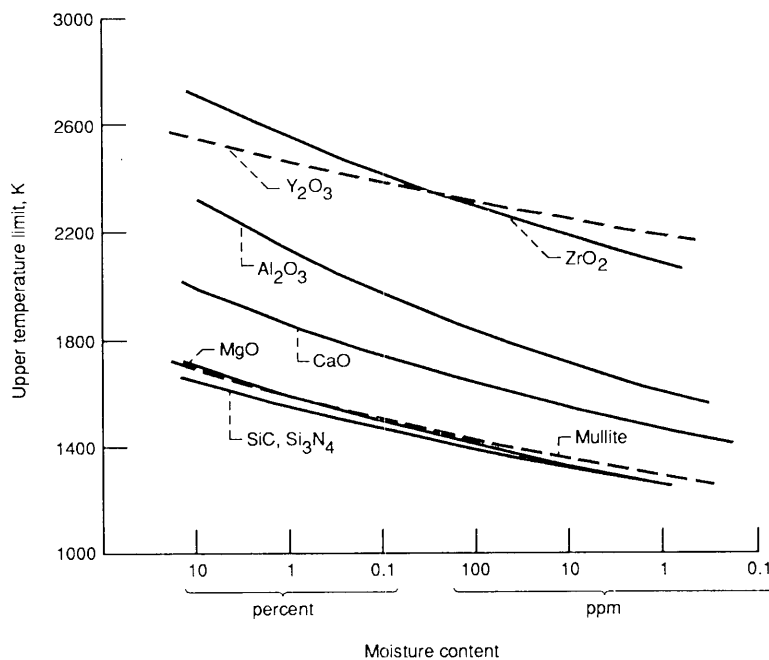
The lower the equilibrium partial pressures for the reaction products are, the longer will be the life of the component. Of course, kinetic factors must be considered in determining the long-term stability of a given material. It is probably reasonable to assume that a total pressure of reaction product gases less than  $10^{-6}$  atm (1 ppm) would pose no long-term serious problems with respect to the degradation of a structural material. On the basis of this assumption the upper temperature limits for different ceramic materials in hydrogen and hydrogen-water environments have been derived.

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Upper temperature limit for ceramic materials in hydrogen atmospheres containing moisture



## Glass-Derived, High-Temperature Superconductors

Potential aerospace propulsion and power applications of high-temperature superconductors generally require high current capability in strong magnetic fields plus the ability to be fabricated into wires. One approach to meeting these needs pursued at NASA Lewis is the quenching of the molten superconductor to a glass followed by crystallization annealing to grow the desired superconducting crystalline phase. Initial studies have focused on the bismuth-strontium-calcium-copper-oxygen system, where glass formation can be readily accomplished. Initial investigations focused on the  $\text{Bi}_{1.5}\text{SrCaCu}_2\text{O}_x$  composition.  $\text{Bi}_{1.5}\text{SrCaCu}_2\text{O}_x$  was prepared in the glassy state by rapid quenching of the melt. The kinetics of crystallization of various phases in the glass was evaluated by variable-heating-rate differential scanning calorimetry. The formation of various phases after thermal treatment of the glass was investigated by powder x-ray diffraction and electrical resistivity measurements. Heating at  $450^\circ\text{C}$  formed  $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ , which disappeared on further heating at  $765^\circ\text{C}$ , where  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  formed. Prolonged heating at  $845^\circ\text{C}$  resulted in the formation of a small amount of a phase with a superconducting transition temperature  $T_c$  onset of  $\sim 108\text{ K}$ , believed to be  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ . This specimen showed zero resistivity at  $54\text{ K}$ .

On the basis of these initial results a melt of composition  $\text{Bi}_{1.5}\text{Pb}_{0.5}\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x$  was fast quenched to form a glass. The glass

was subsequently air annealed, and the influence of annealing time and temperature on the formation of various crystalline phases was investigated. X-ray powder diffraction indicated that none of the resulting samples were single phase. However, annealing at  $840^\circ\text{C}$  increased the volume fraction of the high- $T_c$  phase (isostructural with  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ ) with annealing time. A specimen annealed at this temperature for 243 hours and then slow cooled showed a sharp transition of approximately  $2\text{ K}$  and a  $T_c$  of  $107.2\text{ K}$ . To our knowledge, this is the highest  $T_c$  yet reported for any superconductor prepared by the glass route.

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## Sintering Model for $\text{SiC}_w/\text{Si}_3\text{N}_4$ Composites

Adding silicon carbide whiskers ( $\text{SiC}_w$ ) to a  $\text{Si}_3\text{N}_4$  matrix should improve the composite's toughness, strength, and creep resistance—but also makes it difficult to obtain high density by pressureless sintering. Compositions that provide excellent sinterable monolithic  $\text{Si}_3\text{N}_4$  do not completely sinter when used as matrix material in whisker-toughened composites (WTC). In WTC such matrix compositions are usually densified by hot pressing or canned hot isostatic pressing. These methods limit the usefulness of the material. Pressureless sintering of  $\text{SiC}_w/\text{Si}_3\text{N}_4$  composites should enable net-shape forming of complex components.

The proper combination of  $\text{Si}_3\text{N}_4$  powder and glass formers for liquid-phase sintering a WTC to full density can be determined experimentally. However, a model that can predict the sinterable composition is desirable, especially when powder, whisker, and additive characteristics change. Also, the WTC should have the same grain size, grain boundary thickness, and glass composition as a good monolithic  $\text{Si}_3\text{N}_4$ . Comparing the two materials would then directly clarify the effect of whisker addition on the properties of  $\text{Si}_3\text{N}_4$ .

At NASA Lewis a model has been developed both to sinter  $\text{SiC}_w/\text{Si}_3\text{N}_4$  composites and to clarify the effect of  $\text{SiC}_w$  additions on  $\text{Si}_3\text{N}_4$ . The model predicts that it should be possible to sinter  $\text{SiC}_w/\text{Si}_3\text{N}_4$  composites to theoretical density. It suggests that previous attempts to sinter  $\text{SiC}_w/\text{Si}_3\text{N}_4$  composites failed because the selected composition led

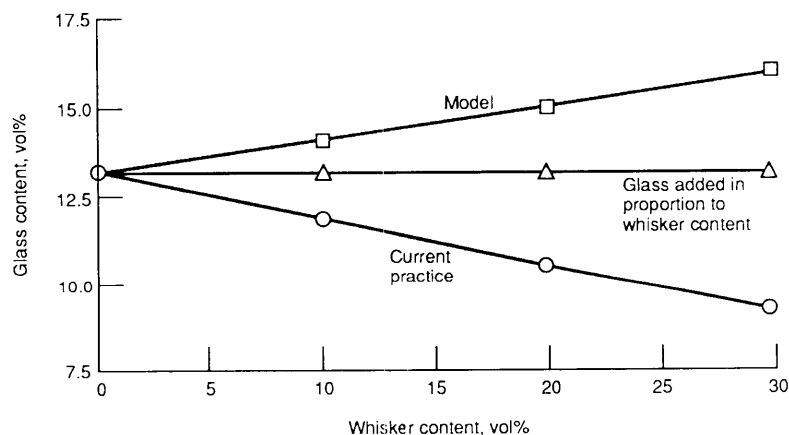
to a "glass deficit." That is, there was not enough glassy grain boundary phase to allow liquid-phase sintering to theoretical density. The model shows that more glass is necessary for sintering a WTC than for sintering an analogous monolithic material. It assumes that additional glass will allow higher whisker loading without forming a constraining network of nonsintering whiskers. However, grain boundary thicknesses in the composite will be less than those calculated for the analogous monolithic material. Therefore, WTC high-temperature properties should not decrease with respect to the monolithic properties despite the increase in glass.

The model suggests that whisker and grain sizes and whisker loading influence the amount of glass necessary to successfully sinter composites. There is a tendency to substitute different whiskers from different manufacturers into the same matrix composition. It is also common to use monolithic  $\text{Si}_3\text{N}_4$  compositions as matrices. The model shows that these are incorrect procedures leading to a decrease in the amount of glass present in the WTC. Maintaining the same volume percentage of glass in the WTC that was present in the monolithic would be an improvement. However, the model predicts a need for additional glass as the whisker loading increases. Current work at Lewis focuses on proving the WTC sintering model. The need for additional glass for sintering WTC has been verified. A WTC containing 30 vol %  $\text{SiC}_w$  was sintered to 95 percent of theoretical density when the model predictions were used to establish composition.

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*Model predicts increase in glass content required to sinter silicon nitride with whisker-toughening phase additions*

### Nondestructive Inspection of Ceramic Composites With Impact Damage

Ceramic materials are leading candidates for high-temperature structural applications, primarily because of their resistance to creep and thermal shock. Fiber reinforcement has been shown to increase the durability of ceramic materials under both static and dynamic loading. Unreinforced (monolithic) ceramic materials can sustain little local damage without complete fracture and a resulting total failure of the component. In contrast, fiber-reinforced ceramics, such as the SiC/reaction-bonded silicon nitride (SiC/RBSN) composites produced at NASA Lewis, are more damage tolerant. The composites can sustain damage from low-energy impact loads without failure.

Impact loading may occur in a realistic engine operating environment when ground debris or atmospheric particles are ingested. Developing impact-damage-tolerant ceramic composites is therefore of critical importance to NASA's high-temperature structures research.

Advanced nondestructive techniques are being developed to detect and analyze damage in ceramic matrix composites caused by impact. Radiographic and ultrasonic inspections of impact-damaged composite panels, when used together, provide a detailed picture of the location and extent of the damage resulting from the impact of a small particle. Thus, proper choice of fiber orientation and composite stacking sequence can control the location, extent, and mode of impact failure.

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*Ultrasonic scan of impacted SiC/Si<sub>3</sub>N<sub>4</sub> test coupon*

## High-Temperature Fatigue Testing of SiC/Titanium Aluminide

Fiber-reinforced titanium aluminides have been identified as an alternative to conventional superalloys for applications requiring a low-density material that maintains its structural integrity at elevated temperatures. NASA Lewis researchers have developed an intermetallic matrix composite with SiC fibers and a matrix of Ti-24Al-11Nb (atomic percent). This material, based on the Ti<sub>3</sub>Al structure, has an excellent high-temperature strength-to-weight ratio and a maximum use temperature of approximately 815 °C. The SiC/Ti-24Al-11Nb composite is fabricated by using a powder cloth technique that ensures full consolidation of the matrix, complete bonding between matrix and fibers, and low oxygen content in the composite. As a part of this research effort the high-temperature mechanical properties of SiC/Ti-24Al-11Nb are being investigated in a high-temperature fatigue and structures laboratory. This work includes the modification of an existing test system used originally for thermo-mechanical experiments on structural alloys, the development of a plate specimen design, the construction of a small two-zone furnace, and the evolution of a specimen gripping method.

A series of strain-controlled fatigue tests conducted on three-ply SiC/Ti-24Al-11Nb at 23, 760, 815 °C have been completed. The results show that temperature has an adverse effect in the low life range (100 to 1000 cycles to failure). However, such an effect is not present in the midlife range (1000 to 10,000 cycles to failure). There appears to be an endurance limit around a strain range of 0.3 percent

for this material. The stress-strain response of all 23 °C tests showed no evidence of damage except for the first quarter and last couple of cycles, but the high-temperature response showed progressive damage throughout the tests. Fatigue lives of this material at 815 °C and the same composition tested by Allison at 760 °C showed little difference even though the oxidation limit for this composite is approximately 760 °C. Thus NASA Lewis' composite has increased the useful temperature range to 815 °C for this type of intermetallic matrix composite without a large change in fatigue life.

Future work will include detailed metallurgical studies on failure mechanisms and further fatigue tests

to fill in high-cycle ranges. Also, a series of fatigue tests at the intermediate temperature of 425 °C will be conducted along with interrupted tests to determine the mechanism of damage and failure.

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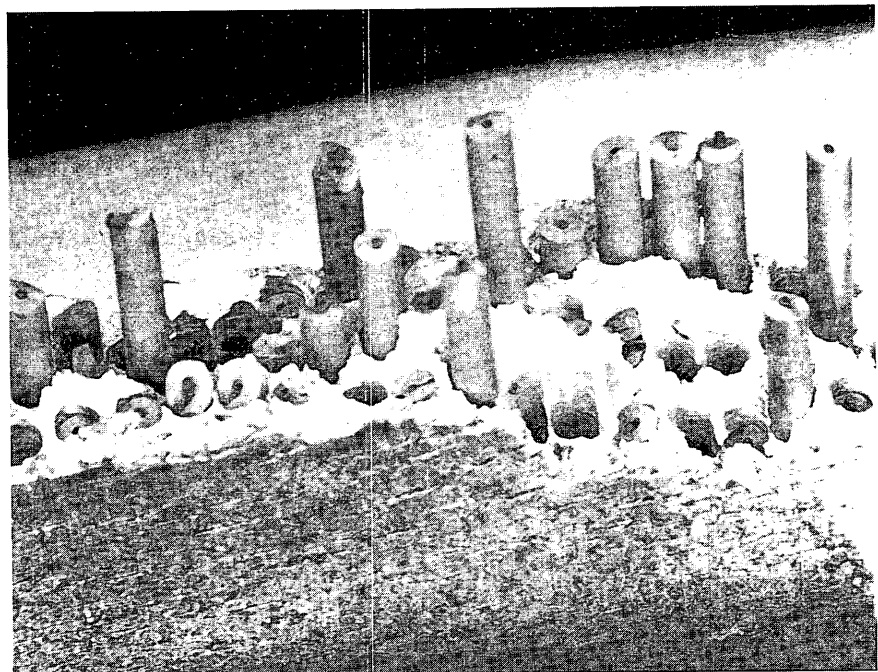
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Brindley, P.K.; Bartolotta, P.A.; and Klima, S.J.: Investigation of a SiC/Ti-24Al-11Nb Composite. NASA TM-100956, 1988.

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*Fracture surface of three-ply SiC/Ti-24Al-11Nb composite tested at 815 °C*

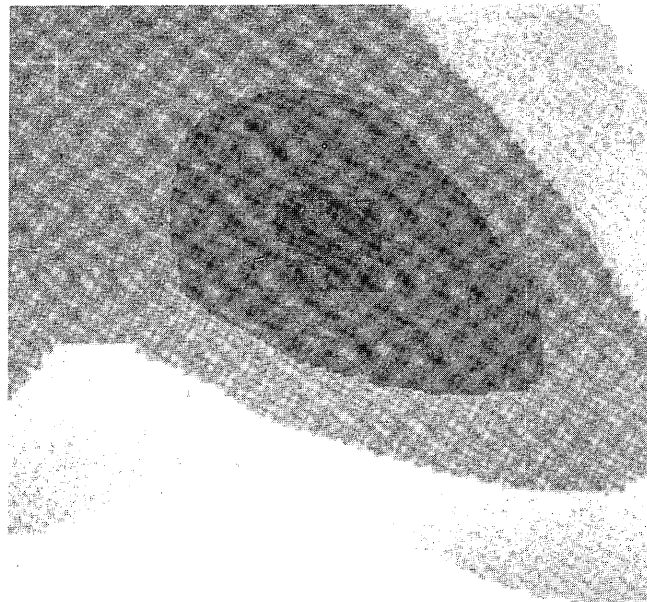
### Nonuniform Transition Conductivity of Superconducting Ceramic

An extensive international research effort is under way into the origin of high-critical-temperature  $T_c$  superconductivity. A considerable amount of this research is directed toward increasing both the critical current density  $J_c$  and  $T_c$ . A better understanding of the mechanisms that support and degrade the superconducting state is required in order to further increase both  $T_c$  and  $J_c$ .

An important difference between ceramic and metallic superconductors is that the microstructural variations throughout bulk superconducting metals are generally small relative to variations in ceramics. For example, porosity and porosity variations exist to a much greater degree in bulk superconducting ceramics.

NASA Lewis has investigated the effect of microstructural variations on the superconducting properties of  $\text{SmBa}_2\text{Cu}_3\text{O}_x$ . A scanning eddy current probe revealed the onset and growth of a normal conducting region in  $\text{SmBa}_2\text{Cu}_3\text{O}_x$  ceramic. Resistance versus temperature measurements taken at different regions of the sample support the concept of a physically mixed state system. Regional nonuniformity of porosity and grain size distributions was found to degrade the superconducting transition by promoting localized Joule heating.

These results indicate that, by controlling the uniformity of the ceramic microstructure, the superconducting properties of these new high-temperature ceramics can be enhanced.



*Eddy current response image of  $\text{SmBa}_2\text{Cu}_3\text{O}_x$  at 90 K  
(darkest area is normal; lightest is superconducting)*

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## Dynamic Porosity Variations in Ceramics

Ceramics and ceramic composites are sensitive to slight microstructural variations. Direct observation and determination of localized failure sites (usually identified as isolated pores, inclusions, agglomerates, anomalously large grains, and poor bond areas) have shown the importance of these material variations as failure-causing factors. The criticality of these factors, often the result of processing variations or processing history, depends on their microstructural and morphological environment.

A silicon carbide disk was sintered from 2090 to 2190 °C in 25-deg C steps. After each sintering step the disk was examined with a precision acoustic scanning system to determine acoustic attenuation and velocity. The attenuation and velocity are directly related to porosity variations within the disk. The bulk density was found to vary nonmonotonically with sintering temperature. The density varied as much as 10 percent from its value at 2090 °C during the sintering process. Local density fluctuations were observed to occur in an organized and history-dependent way. These local density fluctuations, which varied up to  $\pm 7$  percent of the bulk density, were made visible by acoustic attenuation and velocity mapping.

These results are being used for modifying ceramic sintering process parameters. This work is being adapted for in-situ monitoring and control of flaw formation in monolithic ceramics and for control of bond quality in composite ceramics.

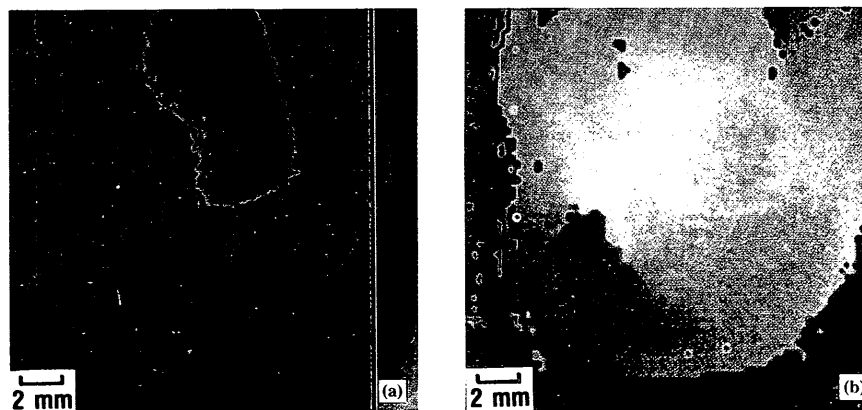
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Changes in local density of sintered silicon carbide sample observed by nonintrusive ultrasonic imaging: (a) initial sintering at 2090 °C, (b) sintering at 2115 °C. High-density regions are light.

### Precision Acoustic Scanning System

The strengths of ceramics and ceramic composites are sensitive to the presence of minute microstructural flaws such as pores. Evaluating these new materials for the presence of flaws requires a technique more sensitive than conventional x-ray radiography.

A precision acoustic scanning system (PASS) has been developed at NASA Lewis specifically for these advanced materials. The PASS yields images of the ultrasonic reflection coefficient of surfaces and ultrasonic attenuation and velocity in solid materials. The reflection coefficient images are representative of surface roughness. The ultrasonic attenuation and velocity images are quantitative indicators of porosity size distribution, porosity gradients, and local porosity fraction in these materials. Porosity variations as small as 0.1 percent can be detected with PASS. This complete, detailed information is not available by any other technique.

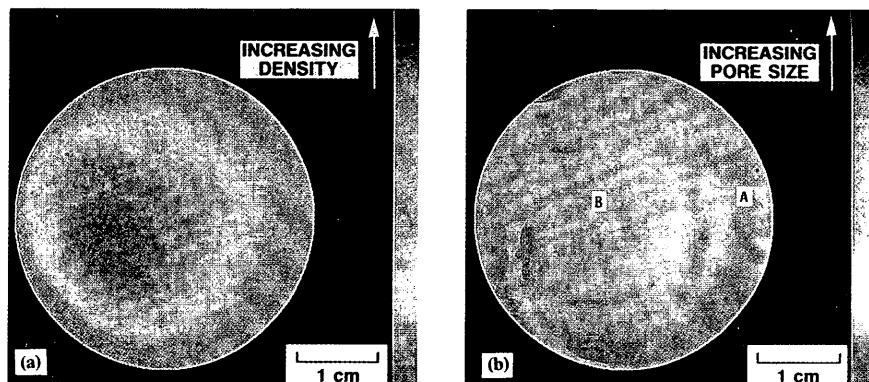
Information provided by PASS is being used to modify and correct sintering process variables.

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*Ultrasonic images of subtle porosity variations (<2 percent) in silicon nitride:  
(a) velocity, (b) attenuation*

## Noninvasive Characterization of Porosity in High-Temperature Ceramic Superconductors

The last several years have seen the remarkable development of a new class of ceramics that exhibit superconductivity to unprecedentedly high temperatures. NASA Lewis recently has assumed an active role in this development.

It is known that microstructural features in ceramic superconductors, such as porosity distribution, second-phase particles, texture variations, and grain boundaries, significantly affect electrical, magnetic, and mechanical properties. Small porosity variations can result in an order-of-magnitude variation in current density and magnetic response. The porosity distribution also affects flux pinning behavior and elastic modulus. Therefore, knowledge and subsequent control of the porosity distribution and its uniformity are vital for the practical application of ceramic superconductors.

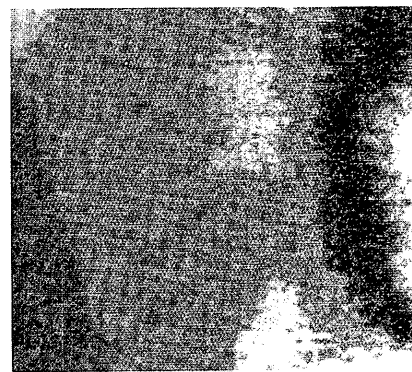
A variety of noninvasive techniques are available for microstructural characterization. A difficulty arises in using noninvasive methods such as ultrasonic imaging and projection radiography when trying to isolate a particular microstructural feature (such as porosity) while masking other features (such as second-phase particles). NASA Lewis has developed a procedure that uses ultrasonic imaging and supplementary material evaluation techniques to isolate the global porosity distribution and to quantify distribution variations for ceramic superconductors.

A precision ultrasonic scanning procedure revealed a subtle porosity variation of approximately 1 percent in a  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  superconductor

specimen. The specimen had been determined from microstructural and chemical analysis to be single-phase, untextured, and free of nonuniform residual microstress. An ultrasonic velocity image constructed from scan data showed relative values of pore concentration. A 1-percent change in ultrasonic velocity is approximately equivalent to a 1-percent change in porosity (density) for this material.

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*Ultrasonic velocity image of ceramic superconductor*



## Structural Mechanics

### Dimensional Analysis for Compliant Impactors

Impact loading is generally categorized as being in either the low, medium, or high velocity regime. The distinction between the different velocity regimes is most aptly made not in terms of absolute velocities, but rather in terms of the type of deformation experienced by the impactor and the target during the impact event. Low-velocity impact is characterized primarily by elastic deformation of impactor and target and highly localized, constrained plasticity only in the material immediately surrounding the point of contact between the two. Classical elastic contact models have been applied successfully to a wide variety of low-velocity impact problems, and this field is quite well developed. Similarly, high-velocity impact has been investigated extensively, particularly during the Apollo spacecraft era and more recently for munitions and space station shielding applications.

The least understood impact regime is the midrange, in which the impact velocity is high enough to cause significant inelastic deformation in the impactor, the target, or both but not high enough to generate the extreme amounts of heat and resulting material phase transformations that can occur during high-velocity impacts. As a result, comparatively few methods are available that can predict with sufficient reliability the response of a structure to an impact loading in the medium velocity regime.

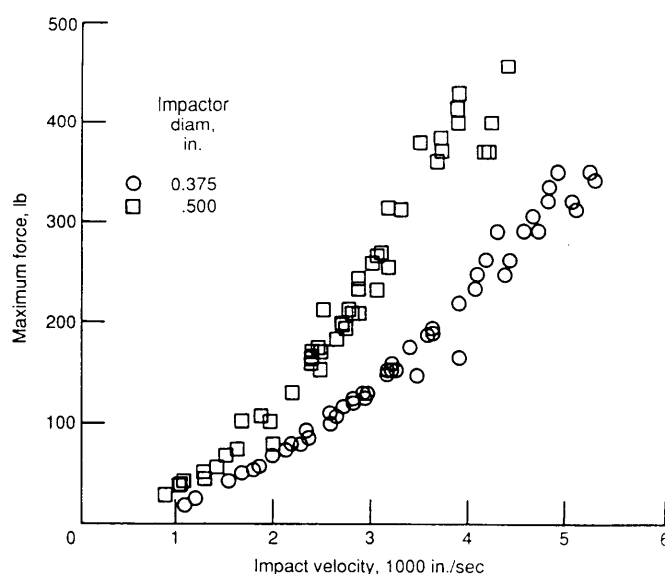
In research conducted at NASA Lewis transient force histories resulting from the impact of compliant projectiles were experimentally measured with an instrumented

target. Results from a series of tests on several different-sized impactors were used to define an empirical impact model that uses four dimensionless parameters to predict, for specified impactor velocity and size, the amplitude, duration, shape, and impulse of the impact force history.

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Variation of amplitude with impact velocity

## Impact Testing of Ceramic Composites

Because advanced gas turbine engines will operate at increasingly higher temperatures for improved efficiency, the continuing development of high-temperature materials for these engines is essential. Engine components are subject to a variety of loading conditions, including impact, which can result from the ingestion of debris. Although the good creep, thermal shock, and oxidation resistance of  $\text{Si}_3\text{N}_4$  make it a suitable material for many high-temperature structural applications, its brittle behavior and low impact resistance limit its efficient use in engine components that may be exposed to impact loading.

Reinforcing reaction-bonded  $\text{Si}_3\text{N}_4$  (RBSN) with high-modulus SiC fibers has been shown to significantly increase its modulus and strength as measured in static tension and bend tests. A "graceful" or ductile-like failure mode was obtained by controlling the strength of the fiber-matrix bond. Similar improvements in the impact behavior of  $\text{Si}_3\text{N}_4$  occur when fiber reinforcement is used. Earlier work investigated the impact behavior of monolithic ceramics, including  $\text{Si}_3\text{N}_4$ , but few data were available on the impact behavior of ceramic composites.

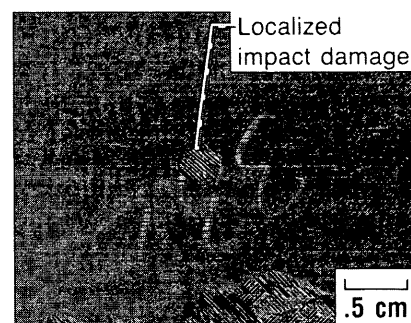
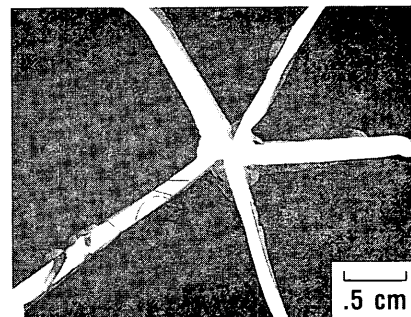
The ballistic impact rig has recently been upgraded to achieve the extremely high data acquisition rates required to accurately measure the dynamic behavior of toughened ceramics and ceramic composites under impact loading.

A series of tests in this facility on SiC/RBSN composites manufactured at Lewis show that a porous surface layer of  $\text{Si}_3\text{N}_4$  increased the impact

resistance of the composite material. As the impact velocity was increased, progressively larger surface indentations occurred and caused an effective local softening of the specimen at the contact point. This distributed the contact force over a greater surface area and over a progressively greater time interval. Because of their hardness, little indentation occurred at subcritical impact velocities in monolithic specimens, and their failure mode was different from that observed for the RBSN composite. Brittle fracture occurred in the monolithic ceramic within the first 5  $\mu\text{sec}$  after impact, at about the same failure strain measured in static bend tests.

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*SiC/RBSN composites (bottom) show better impact resistance than monolithic ceramic (top)*

## Computational Simulation of Delaminations in Fiber Composites

Free-edge regions and discontinuities in composite laminates are often sites at which steep interlaminar stress gradients are present. These steep stress gradients are intrinsic to the anisotropic heterogeneous structure of the laminate (where plies are oriented in different directions) and develop when the laminate is subjected to mechanical loads, environmental loads, or both. Interlaminar stresses are important considerations in laminate design because they contribute to fatigue degradation of the laminate by causing delamination extensions.

NASA Lewis has developed a procedure to computationally simulate composite laminate fracture toughness in terms of strain energy release rate and to evaluate the degradation in laminate structural integrity in terms of displacements and losses in stiffness, vibration frequencies, and buckling resistance. Specific laminates were selected for detailed studies to demonstrate the generality of the procedure. These laminates have center (midplane) delaminations, off-center delaminations, and pocket delaminations (center and off center) at the free edge and center delaminations at the interior. The laminates have two different thicknesses and are made from three different materials. The results obtained illustrate the effects of delaminations on the laminate structural integrity and on the laminate strain energy release rate (composite fracture toughness).

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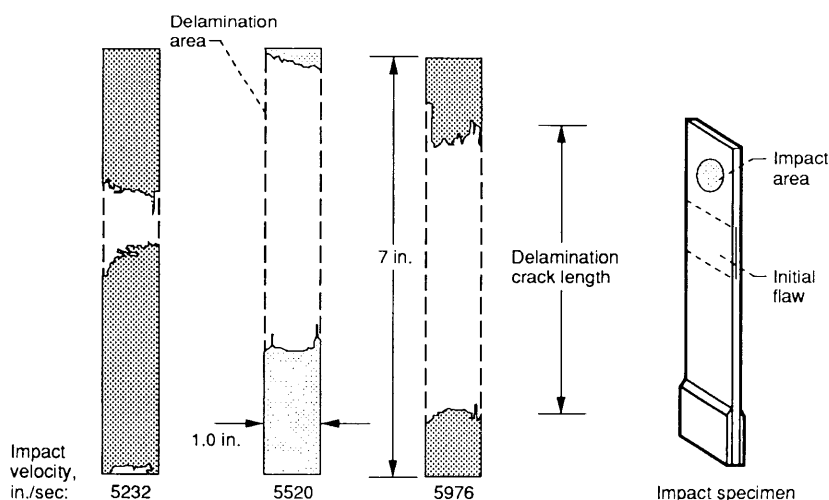
## Vibration Properties of Damaged Composite Laminates

Efficient use of advanced composite materials requires that in-service components be able to retain their structural integrity even if they contain internal flaws or defects of some nominal size. In composite materials such flaws can result from fatigue, periodic overloading, or even impact during normal use; or they can be inadvertently introduced during the fabrication process. Vibration properties are critical when lightweight structural components are used in modern aerospace applications.

A new vibration test rig was recently designed and built as part of an ongoing in-house research effort to experimentally and analytically evaluate the effect of damage on the structural properties of advanced composite materials. The rig was used to conduct a series of postimpact vibration tests on composite laminates damaged by transverse impact. A decrease in stiffness, such as that caused by

impact damage, results in a corresponding decrease in the natural frequencies of the damaged composite structure. To determine the extent of this effect, the first four natural frequencies of a series of cantilevered graphite/epoxy composite specimens with initial embedded delaminations were measured before and after impact. The measured reduction in these natural frequencies for varying amounts of impact damage compared well with the results of a two-dimensional finite element simulation of the damaged specimens. The results indicate that the finite element representation accurately models the low-vibration modes of both damaged and undamaged specimens. In addition, the higher frequencies are progressively more sensitive to delamination damage.

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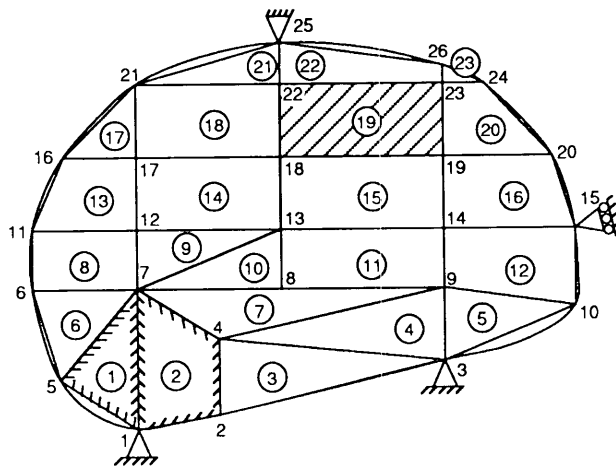
*Ultrasonic C-scans show postimpact delamination crack length*

## Integrated Force Method for Finite Element Analysis

The two most fundamental approaches for analyzing finite element models of structures are the force method and the displacement method. The details of these methods were intensively investigated three decades ago during the early evolution of computer automation of structural analyses. As is well known, the displacement method won out for computer automation. The force method available at that time was based on the concept of redundant selections. Because it was the result of approaches developed in the precomputer era, it proved inconvenient to automate and was computationally more costly.

A new version of the force method termed the "integrated force method" (IFM) has been introduced recently. The IFM integrates the system equilibrium equations and the global compatibility conditions in a fashion paralleling the Beltrami-Michell formulation of elasticity. The IFM is as convenient to automate as the displacement method.

A project to compare the integrated force and displacement methods concluded that the IFM operates directly on stress parameters, providing potentially more accurate results; its equations form a well-conditioned system; a discrete analysis solution converges to the correct solution more rapidly by IFM; IFM solutions can be obtained in less computation time; and initial deformation problems are more elegantly treated by IFM.



*Finite-element model*

The integrated force method was also compared with the mixed methods including the MHOST code. IFM converged more rapidly than the mixed methods.

This research indicates that with further development the IFM can become a robust and versatile analysis formulation and a viable alternative to the popular displacement method.

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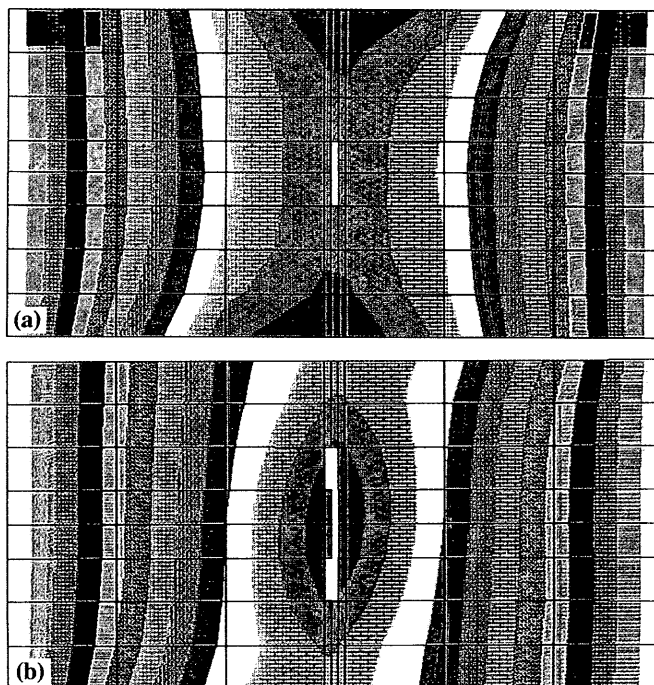
## Structural Behavior of Composites With Progressive Fracture

An attempt has been made to unify the computational tools developed at NASA Lewis for predicting progressive damage and fracture with the prediction of the overall response of damaged composite structures. In the present approach the computational model for the damaged structure is constructed by a computer program as a byproduct of the analysis of progressive damage and fracture. The combined numerical procedure is amenable to development as a nondestructive method for evaluating the structural integrity of multiple-ply composites. Structural characteristics such as natural frequencies and buckling loads with corresponding mode shapes are investigated during progressive fracture of multilayer angle-ply composite structures. Variations in structural characteristics as a function of the previously endured loading are studied. The nature of structural change with damage varies with laminate configuration, fiber orientation, and boundary conditions.

An intermediate-stiffness T-300/epoxy composite structure was selected for initial investigations. The structure was analyzed under a gradually applied uniform axial tensile loading. Progressive damage and fracture were monitored as the applied loading was increased. As the composite structure deteriorated under loading, its overall response properties, such as natural frequencies and buckling loads with the associated mode shapes, degraded as well. For example, a plate structure experienced a decline in the first three natural frequencies and in the fundamental buckling load as a function of the load endured. The variation in the detailed

composite behavior in the several cases studied indicates that general conclusions regarding the behavior of damaged composites remain elusive and that there is no simple generalization or rule relating the degraded structural characteristics of damaged angle-ply composite structures to the actual amount of damage present in the composite material. Accordingly, the necessity of reliable computational composite mechanics to predict the significant structural behavior patterns for each type, laminate, fiber orientation, geometry, boundary condition, and loading of a composite structure is reacknowledged.

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Vibration mode 1: (a) before loading, (b) after 95 percent of ultimate failure load was applied

## Probabilistic Composite Micromechanics

The properties of composite laminates depend on the properties of the constituent materials and their distribution and orientation. Laminates are composed of layers of unidirectionally reinforced plies (lamina). The ply is typically considered the basic unit of material in composite mechanics. The branch of composite mechanics that predicts ply material properties based on the properties, volume, and orientation of its constituents is known as composite micromechanics and frequently incorporates the traditional mechanics-of-materials assumptions. The integration of ply properties to yield laminate properties is called laminate theory. Laminate variables such as ply orientation and stacking sequence can be tailored to yield a laminate with the desired material properties. Thus, the laminated composite is a suitable material for component design.

Fiber composite structures are currently analyzed by using a variety of computer codes. Complete mechanical, thermal, and hygral properties are calculated and can be used to compute respective structural responses. Advanced failure criteria are used to calculate composite strengths. Environmental effects are also quantified. The analytical capability of these codes is limited by the deterministic nature of the computations, and corresponding measured data exhibit considerable scatter. Specifically, fixed values for constituent material properties, fabrication process variables (i.e., constituent volume ratios), and internal geometry are used as input. However, random variations in these parameters are not only expected, but easily observed experimentally.

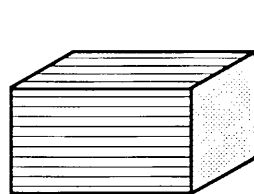
Analyzing composite structures requires reliable predictive models for material properties and strengths, but prediction efforts have been complicated by inherent scatter in experimental data. Since uncertainties in the constituent properties, fabrication variables, and internal geometry would lead to uncertainties in the measured composite properties, the following question arises: How much of the "statistical" scatter of experimentally observed composite properties can be explained by reasonable statistical distribution of input parameters (primitive variables) in composite micromechanics and laminate theory predictive models?

In order to answer this question, a study was conducted to develop a probabilistic approach to composite micromechanics that simulates uncertainties in unidirectional fiber

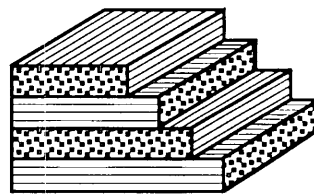
composite properties. The approach is in the form of computational procedures using Monte Carlo simulation. The variables for which uncertainties are accounted include constituent and void volume ratios, constituent elastic properties and strengths, and fiber misalignment (primitive variables). A graphite/epoxy unidirectional composite (ply) is used to incorporate fiber composite material property uncertainties at the micro level.

Probabilistic composite micromechanics provides extensive information that formally relates ply phenomenological behavior to a large number of complex and interacting uncertainties at the constituent level.

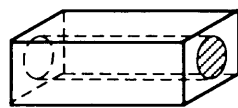
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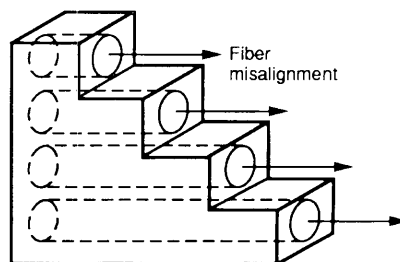
Orthotropic ply



Laminate



Subply



Ply

Ply substructuring

## Mechanics of Composite Materials: Past, Present, Future

Composite mechanics has evolved to encompass a wide range of continuum and discrete mechanics methods. These methods are used to study and predict fiber composite behavior. The composite behavior is studied or predicted at various inherent scales (corresponding to the fabrication processes) in the composite from microstructure to structural response. Within each inherent scale a specialty composite mechanics discipline with several levels of sophistication has evolved. These levels of sophistication were influenced by three important factors: capturing the intrinsic physics, the degree of local detail desired, and the technical interests of the investigator. Collectively, these three factors have led to numerous significant contributions at the various scales of composite behavior.

A survey was recently prepared at NASA Lewis to describe composite mechanics at its various levels of sophistication and attendant inherent scales of application with respect to the past, present, and future. The survey was intended to stimulate thinking and perhaps lead to "revolutionary" research. The survey was organized as follows: (1) inherent scales, (2) disciplines, (3) levels of sophistication, (4) factors influencing discipline, scale, and level of sophistication, (5) discriminators between alternative methods of determining levels of sophistication, (6) where has it been? (7) what has it accomplished? (8) where is it headed? and (9) where should it go?

Examples mainly taken from in-house research over the years were used to supplement and complement the survey. However, they are represen-

tative of the evolution of composite mechanics during that period.

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Chamis, C.C.: Mechanics of Composite Materials: Past, Present, and Future. NASA TM-100793, 1989.

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Discipline	Research conducted	Success (understood or quantified)	Application
Composite micromechanics	Considerable	Partial	Limited
Composite macromechanics	Negligible	Exceptional	Extensive
Combined stress failure	Minimal	Noticeable	Extensive
Laminate theory	Considerable	Acceptable	Extensive
Singularity mechanics	Substantial	Promising	Limited
Life (durability)	Substantial	Promising	Limited
Structural mechanics	Minimal	Highly acceptable	Extensive

### *Composite mechanics—where has it been and what has it accomplished?*

Discipline	Effort (approach)	Where it should go
Composite micromechanics	Negligible (traditional)	Fracture initiation and propagation
Composite macromechanics	Negligible (classical)	Combined mode fracture and mode tracking
Combined stress failure	Negligible (classical)	In-situ ply strengths and failure mode branching
Laminate theory	Nonlinear (conventional)	Computational efficiency and three-dimensional behavior
Singularity mechanics	Extensive homogeneous anisotropy (classical)	Local heterogeneity and nonlinearity
Life or durability	Progressive fracture (semiconventional)	Hygral, thermal, mechanical and temporal aspects properly and tractably integrated
Structural mechanics	Familiarity with available general-purpose finite element codes (user mode); limited development	Development of composite mechanics specialty finite elements and substructuring methods

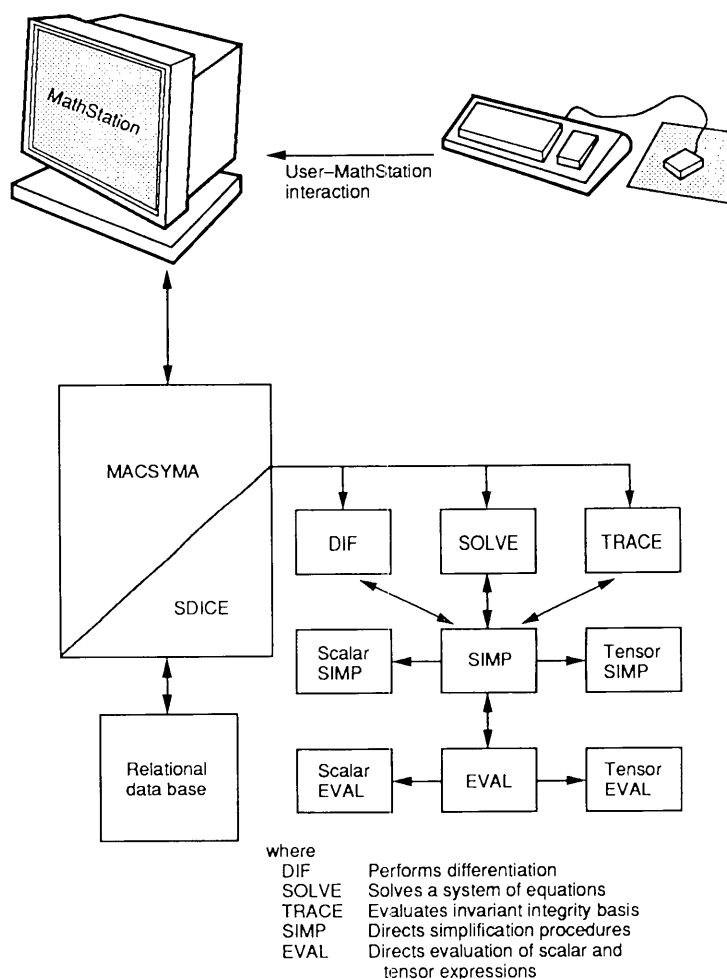
### *Composite mechanics—Where is it headed? Where should it go?*

## SDICE: Expert System for Symbolic Derivation of Potential-Based Constitutive Equations

Structural alloys used in high-temperature applications exhibit complex thermomechanical behavior that is inherently time dependent and hereditary, as the current behavior depends not only on current conditions but also on the thermo-mechanical history. Derivation of mathematical expressions (constitutive equations) that describe this high-temperature material behavior can be quite time consuming, involved, and error prone. Intelligent application of symbolic systems to facilitate this tedious process can thus be of significant benefit. This is particularly true when dealing with anisotropic materials such as metal matrix composites, since automating the derivation process becomes crucial for developing new theories beyond those of a single preferred direction.

The direct use of a general-purpose symbolic computation system such as MACSYMA to derive flow and evolutionary equations is not productive because a large number of steps are involved in the derivation process and problems are associated with expression growth. Resourceful derivation procedures must be developed so that optimal results can be obtained. A problem-oriented package (named "SDICE"), running under MACSYMA and capable of efficiently deriving these constitutive equations in analytical form, is presently being developed at NASA Lewis. The initial public release date is December 1989.

The uniqueness of SDICE resides in its ability to simulate the human intelligence (interaction) needed to derive the required constitutive relations (in simplified form) when



SDICE system and data flow chart

accessing the basic algebraic and calculus functions provided by MACSYMA. Other features are its ability to calculate and manipulate tensors in index notation, to calculate the invariant integrity basis, and to determine history-independent, nonphysical coefficients in terms of physically measurable ones.

Immediate benefits can be realized from the development of SDICE. The tedium of manual calculations is lessened. The reliability of the derived equations, and hence of the final analysis results, is increased. Model development time is shorter, and alternative functional forms can be more easily studied.



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**Viscoplasticity: A Thermodynamic Formulation**

NASA Lewis and the Office National d'Etudes et de Recherches Aeronautiques (ONERA) in Chatillon, France, are currently engaged in a cooperative agreement involving exchanges in personnel. The agreement is intended to further the theoretical development, and our physical understanding, of inelastic material response and damage accumulation as represented by the theories of viscoplasticity and damage mechanics. During the first exchange a thermodynamic formulation was advanced for a general theory of viscoplasticity.

Within the framework of Coleman and Gurtin's continuum theory of thermodynamics with internal state variables, a general theory of viscoplasticity has been developed. Three fundamental internal variables are used in various combinations in viscoplastic models found in the literature and have therefore been incorporated into our general theory. They are the tensor-valued backstress to account for kinematic hardening effects, and the scalar-valued yield and drag strengths to account for isotropic hardening effects. Each of these three fundamental internal state variables can comprise a sum of separately evolving constituents, each with its own characteristic time. For example, two backstresses may be considered. One could be long-range backstresses due to larger dislocation substructures such as grain boundaries and cell walls; the other could be short-range backstresses due to smaller dislocation substructures such as dislocation bowing and entanglements. Each separate constituent is taken to evolve phenomenologically through

competing mechanisms of strain hardening, dynamic (strain induced) recovery, and static (thermal time induced) recovery in accordance with material science. The theory is general, leaving the modeler to determine which internal state variables to incorporate into his or her model, the number of separate constituents needed for the applications, and what form the material functions should take in the evolution of inelastic strain and in the hardening/recovery terms of the evolution equations for the material's internal state variables.

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## **Nonlinear Mesomechanics of Composites With Periodic Microstructure**

A theoretical development concerned with modeling the mechanical deformation or constitutive behavior of composites with periodic microstructure under small displacement conditions at elevated temperatures is under way. A mesomechanics approach is adopted that relates the micromechanical behavior of the heterogeneous composite with its in-service macroscopic behavior.

Two different methods, one based on a Fourier series approach and the other on a Green's function approach, are used in modeling the micromechanical behavior of the composite material. These formulations have been shown to be equivalent in the infinite-body problem. Each constituent phase can have elastic, thermal, and inelastic (e.g., viscoplastic) strains. Although the constitutive formulations of the composite are based on a micromechanical approach, it should be stressed that the resulting equations are volume averaged to produce overall "effective" constitutive relations that relate the bulk volume-averaged stress increments to the bulk volume-averaged strain increments. As such, they are macromodels that can be used directly in nonlinear finite element codes for structural analysis.

In developing the volume-averaged or "effective" macromodels from the micromechanical models, both approaches (i.e., Fourier series and Green's function) require the evaluation of volume integrals containing the spatially varying strain distributions throughout the composite material. By assuming that the strain distributions are spatially constant

within each constituent phase—or within a given subvolume within each constituent phase—of the composite material, the volume integrals can be obtained in closed form. This simplified micromodel can then be volume averaged to obtain an "effective" macromodel suitable for use in a nonlinear finite element code to obtain the strain-temperature history at critical damage locations in the structure. The "exact" micromechanical models can then be used outside the finite element program to evaluate the heterogeneous stress-strain history throughout each constituent phase of the composite material. This variation must be known in order to evaluate the damage history variation.

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### Advanced Thermomechanical Testing of High-Temperature Structural Alloys

NASA Lewis has developed capabilities for conducting thermomechanical experiments on high-temperature structural alloys under closely controlled conditions. In these experiments temperature as well as stress and strain is cycled to more closely simulate conditions experienced during power generation. Precise control is achieved through specialized servohydraulic test systems and state-of-the-art computer control. Advanced heating systems and innovative experimental techniques are used to eliminate difficulties traditionally associated with dynamic temperature control and phasing. It has therefore proved possible to study thermomechanical response in complex structural alloys for the first time with minimum experimental uncertainty.

One such investigation was recently completed on Hastelloy-X, a material currently used in the hot section of gas turbine engines. This material is of particular research interest as a result of metallurgical instabilities experienced over the temperature range 400 to 600 °C. These instabilities give rise to complex hardening behavior under both isothermal and thermomechanical loading conditions. This behavior has proved difficult to characterize and resulted in questionable deformation models and uncertain life predictions.

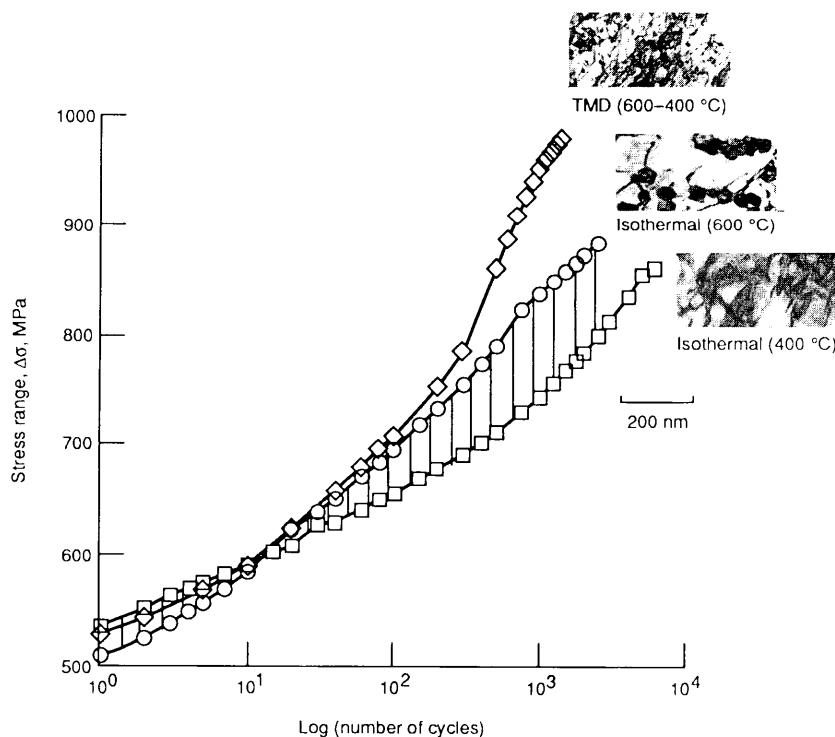
In an effort to further investigate this complex behavior, a series of carefully controlled in-phase and out-of-phase thermomechanical tests were conducted where the mechanical component of strain matched that of earlier isothermal tests. Direct

comparison over the temperature range of interest, 400 to 600 °C, revealed that the thermomechanical response was not bounded by the isothermal data. This result highlighted the need for reliable thermomechanical data when developing theoretical models.

A viscoplastic constitutive model is being developed to mathematically describe thermomechanical behavior. The model utilizes three internal state variables, one of which treats metallurgical instabilities of the type

evidenced by Hastelloy-X. Detailed metallographic studies are also being conducted on this material; the information is being used to establish a physical basis for the theoretical modeling. It is anticipated that this balanced approach will lead to improved thermomechanical life prediction techniques and, ultimately, better hot-section performance.

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*Thermomechanical response of Hastelloy-X*

## Subcritical Crack Propagation in Brittle Composites

Incorporating ceramic whiskers within a monolithic ceramic matrix improves the overall toughness of the resulting material—it has long been thought by spanning the crack tip and thereby reducing the induced stress singularity. However, a growing body of experimental evidence suggests that the toughening is primarily enhanced by the deflection of the crack tip as it propagates through what amounts to a heterogeneous strength field. Success in using these toughened ceramic composites will rely strongly on developing adequate design methodologies and strength characterizations. Design approaches must formally address material heterogeneity and crack deflection in a manner consistent with the nature of fracture in ceramic composites.

Current design methodologies propose probabilistic approaches that use the weakest-link theory to account for failures produced by the inherent heterogeneity of brittle materials. Most of these models assume that the failure of an entire volume is determined by the independent failure of an elemental volume. Independent failure models inadequately account for the interaction of a main crack with material heterogeneity or the possibility of load shedding due to microstructural redundancy.

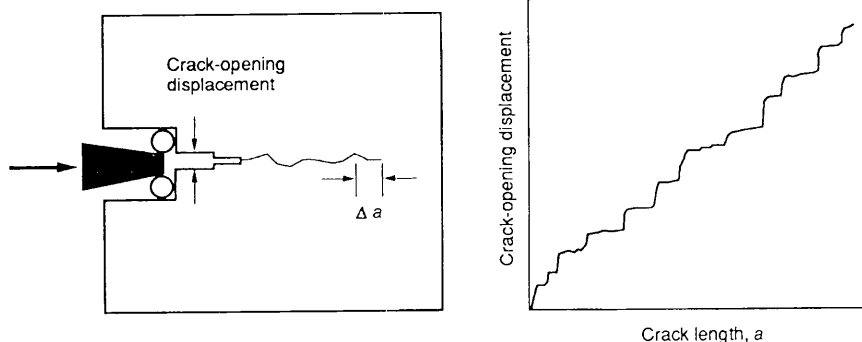
NASA Lewis' cooperation with researchers at the University of Illinois at Chicago has contributed to the development of a design approach that directly addresses crack interaction with material heterogeneity. The conditions for global failure of a structural volume are precipitated by the interdependent failure of

elemental volumes. The design approach assumes that the equivalent fracture surface energy is a random variable that follows a weakest-link, or Weibull, distribution. The strength-field distribution is manifested by a crack that propagates locally through an optimum path of minimum fracture surface energy and maximum driving force. Individual crack trajectories are modeled as one-dimensional Brownian motion, and crack propagation is a diffusion process.

Application of the crack diffusion theory is being experimentally investigated through subcritical crack

propagation studies in silicon-carbide-whisker-reinforced alumina. A sharp, straight-through crack is propagated subcritically by controlled displacement loading at the crack mouth. Recorded data reveal that crack advance occurs as discrete jumps. These discrete jumps are used to characterize the material and together with the crack diffusion theory can be used to predict failure probabilities in separate tests for verification.

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*Subcritical crack propagation in brittle composites*

## Ultrasonic Imaging of Textured Alumina

Research at NASA Lewis has related the texture of a ceramic material to ultrasonic pulse-echo measurements of specimens made from the material. Fracture characteristics have been found to be influenced by texture. Precision ultrasonic velocity and attenuation scans reveal this subtle microstructural feature.

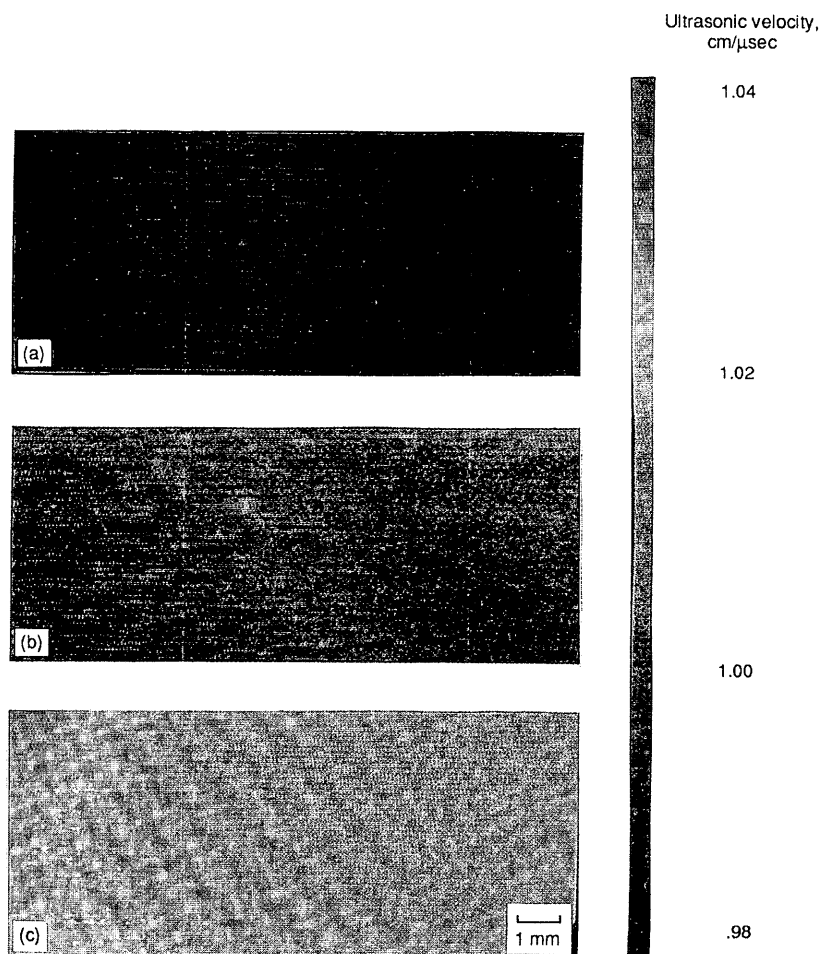
Two sets of specimens were used. One set was isostatically pressed and the other extruded. The pores and grains were of similar size for both materials, but there was a slight elongation (texture) parallel to the extrusion axis in the extruded material. Both the fracture toughness and the crack growth resistance of the extruded samples were found to vary with test orientation. The toughest samples (40 percent tougher than isopressed material) were those oriented such that the extrusion direction was perpendicular to the direction of crack growth. The crack growth resistance was also greatest in these samples.

Fractured specimens were machined into 4-mm-thick blocks, and ultrasonic pulse-echo data were obtained with a precision contact-scanning technique. Images of bulk velocity and attenuation were then found. Although bulk density was similar for all samples, their anisotropy (texture) was revealed. The samples with notably higher velocity (5 percent greater than the isopressed samples) had the direction of sound propagation parallel to the extrusion axis. Images of the extruded samples where the direction of propagation was perpendicular to the extrusion axis showed variations due to extrusion-caused irregularities.

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*Ultrasonic velocity of three alumina samples: (a) isopressed, (b) wave propagation perpendicular to extrusion axis, (c) wave propagation parallel to extrusion axis*

## Probabilistic Pressure Vessel Design Methodology

The ability to design static structures and rotating machine components that can survive anticipated loads and stresses in both normal and overload applications is an important safety and economic requirement. Common design practice for many industrial applications tends toward placing large safety factors in the design of structures and machinery. Although this practice results in satisfactory operation, usually the machine element is large and heavy and uses materials inefficiently. An alternative is to design structural elements to operate at loads closer to their failure strength and then proof test the end product to ensure the safety of those items that will reach the consumer. However, this method can also be costly, perhaps more so than designing with a conservative safety factor.

In aerospace applications, designing in a conservative mode with large safety factors is precluded because the resultant structure would be either too heavy or too bulky to fly. Hence, designing closer to the failure limit is almost mandatory in aerospace applications. The issue becomes one of how to determine the failure limit of a structure or a machine element.

A further issue confronting the engineer is the determination of the stress in a structure below which no fatigue, creep, or fracture failures will occur. Elaborate sets of standards have been developed for pressure vessels that ensure, with reasonable engineering certainty, that for known materials no failure will occur over the usable design life. However, for new or untested materials for which no field

experience exists, how should this determination be made? What kind of tests should be conducted? How many specimens should be run? How can results from coupon specimens be extrapolated to full-size structures? How can the probability of survival of a structure subjected to known loads be determined with reasonable engineering certainty?

In order to answer these questions, the fracture strengths of two large batches of A357-T6 cast aluminum coupon specimens were compared by using two-parameter Weibull analysis. The minimum number of these specimens necessary to find the fracture strength of the material was determined. The applicability of three-parameter Weibull analysis was also investigated. A design methodology

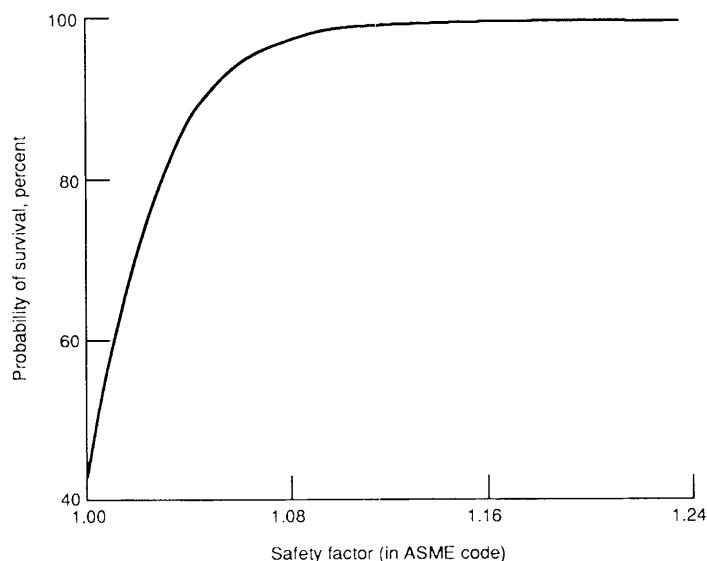
based on the combination of elementary stress analysis and Weibull statistical analysis was advanced and applied to the design of a spherical pressure vessel shell. The results from this design methodology were compared with results from the applicable American Society of Mechanical Engineers pressure vessel code.

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*Correlation between probability of survival and safety factor for spherical pressure vessel shell: fracture strength of A357-T6 cast aluminum (handbook value), 310 MPa (45 ksi)*

### Unified Micromechanics of Damping for Composite Plies

A complete micromechanics theory has been developed for all six damping coefficients of a composite ply associated with the following local stresses: longitudinal, transverse, through-the-thickness normal stress, in-plane shear, through-the-thickness (1-3) shear, and through-the-thickness (2-3) shear. The six composite damping capacities are synthesized from the hysteretic damping of matrix and fibers and from interface friction. The effect of moisture and temperature on composite damping is included. In addition to hysteretic damping the present method includes the contribution to the overall composite ply damping of interfacial friction damping due to broken fibers. Off-axis specific damping capacities (SDC's) (i.e., the SDC's of a ply loaded at an off-axis angle) are also synthesized from the on-axis SDC's. The transformation for this purpose has been developed. The temperature rise in composite plies subjected to cyclic vibration is also predicted. Because temperature variations affect the performance of composite materials, knowledge of the developed temperature profiles in vibrating composite plies is desirable.

The micromechanics theory has been augmented into an in-house computer code. Predicted results compare well with available experimental measurements reported in the open literature. All SDC's are sensitive to fiber volume ratio, with the exception of the longitudinal on-axis SDC. In view of the sensitivity of composite damping to micromechanics parameters, the present theory is a valuable approach for selecting suitable fiber-matrix combinations and fiber volume ratios in order to

satisfy particular damping requirements. Off-axis-ply SDC's vary widely with respect to fiber angle, indicating that ply angles may be an effective design parameter for tailoring the damping capacity of composite plies. Temperature and moisture variations significantly influence the damping capacity of composite plies. Interfacial friction damping contributes to the overall damping capacity of unidirectional composites, and its contribution is more significant in the case of off-axis loading.

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### Shape Optimal Design of Elastic Bodies

Shape optimal design is a problem that has interested many researchers in the last 15 years. Zienkiewicz and Campbell were about the first to approach this problem by using a virtual displacement-based finite element method. Subsequently, this method has been applied widely to problems in shape optimal design, but only with mixed success.

NASA Lewis has developed a variational formulation and procedure to compute an optimal design shape for two-dimensional linear elastic bodies by using a mixed finite element formulation. In some situations mixed finite element methods provide a more accurate computation of stresses and strains at the element nodes than the virtual displacement technique. Hence, the structure at each optimization iteration is modeled more accurately, and an improved structural shape results.

The optimality criterion used herein was to minimize the maximum value of the Von Mises equivalent stress (or other suitable stress measure) in the body subject to an isoparametric constraint on the area.

In the finite element implementation of this technique an elliptical automatic mesh generator that ensured an orthogonal finite element mesh at the domain boundary was used at each shape redesign. Use of this mesh generator avoided the increase in finite element error caused by mesh distortion during shape redesign and therefore prevented the convergence instabilities experienced in previous optimization studies.

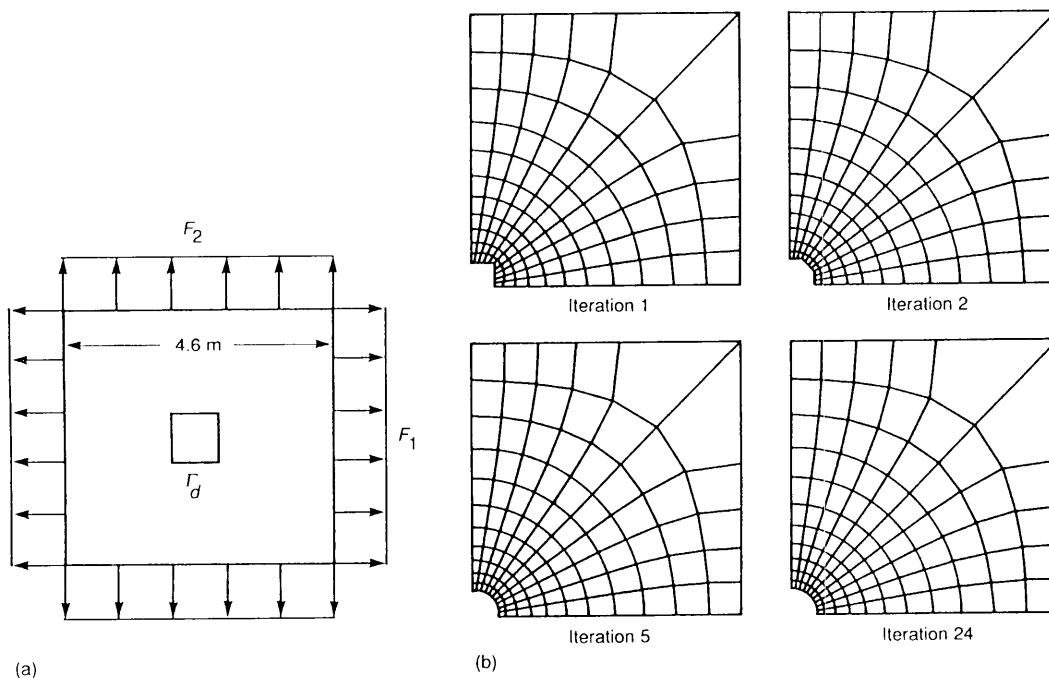
The analysis technique has been tested with several classical shape

optimization problems including optimization of a hole in a square sheet. A sheet with an initial square hole was loaded along its vertical and horizontal faces with equally distributed forces. The required hole area was specified by the user. The optimization executed automatically, alternating between evaluating element stress-strain levels and reshaping the hole subject to the optimality criterion, until the hole's area matched the specified area within some tolerance band. For the applied symmetrical loading the initial square hole converged to a circular hole as expected for the specified optimality criterion. The

maximum Von Mises stress within the body was reduced to just over one-third of its original level.

This numerical example, among others, demonstrated that the solution procedure converges to expected shapes in a stable manner, overcoming problems commonly encountered in shape optimization when instabilities develop in the design boundary definition.

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Shape optimal design of hole in square sheet: (a) dimensions of initial input,  
(b) variations of shape during iterative procedure



## Distributed Finite Element Analysis Using a Transputer Network

Finite element analysis is used extensively in evaluating the load and life capabilities of structures from small to large and simple to complex. Complex structures with thousands of independent degrees of freedom are typically analyzed on expensive supercomputers to achieve reasonable computational time. However, the performance of supercomputers can be approached and even exceeded with parallel-processing networks of low-cost processors.

Under a Small Business Innovation Research contract with NASA Lewis, Sparta, Inc., developed a desktop parallel-processing workstation capable of supercomputer performance. The workstation consists of a network of 32 interconnected transputers operated from an IBM PC/AT-compatible host computer. It also has a large-screen color graphics system and a network mass storage system.

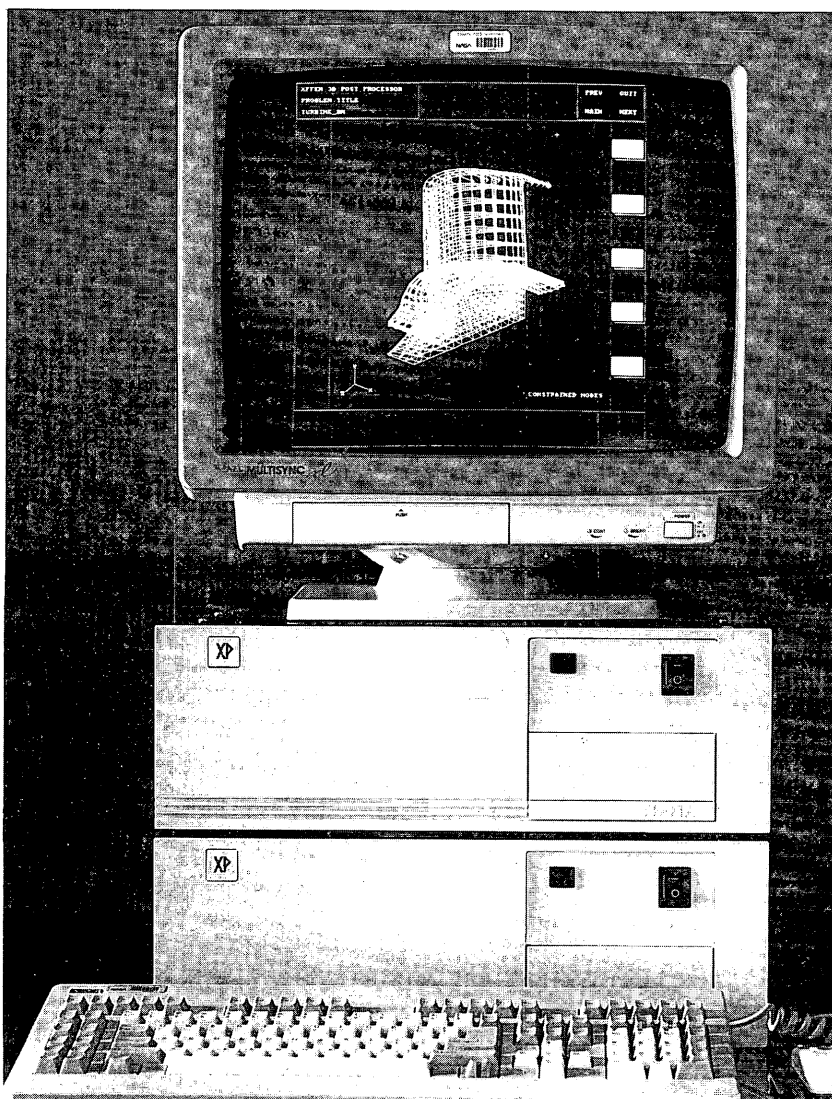
The INMOS T800 transputers used in the workstation are powerful computers with processors, memory, and communications capability contained on a single 1-in.-square chip. Each transputer has four two-way communications links that can be connected to other transputers in a wide variety of network architectures.

A space shuttle main engine turbine blade model was used to demonstrate the capability of the workstation. The blade model had about 1500 nodes and 4500 independent degrees of freedom. A linear static analysis similar to NASTRAN was implemented on the workstation. The workstation executed the analysis at about one-

third the speed of a Cray X/MP24. This gives the workstation a cost-performance ratio about 60 times better than the Cray system.

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Desktop parallel-processing workstation

## Life Prediction

### Composite Fatigue Using Loading Stage in Scanning Electron Microscope

Improving the methodology for predicting the life cycle of advanced structural components requires knowledge of the micromechanical behavior of the composite materials from which such components are manufactured. The difficulties in modeling fatigue damage in these highly anisotropic and nonhomogeneous materials have proven to be the major stumbling block in the development of new and improved life prediction models.

The recently developed in-situ loading stage inside a scanning electron microscope at NASA Lewis can be used to overcome such obstacles. The loading stage allows real-time, high-magnification (up to 10,000 times) viewing of dynamically or statically loaded aerospace materials. A maximum cyclic load of 1000 lb can be applied. Two types of specially designed grips allow both pin and friction loading. A built-in extensometer mounted to the test specimen provides load-displacement data, which can be stored through either digital or analog means. The video signal can be videotaped for further analysis.

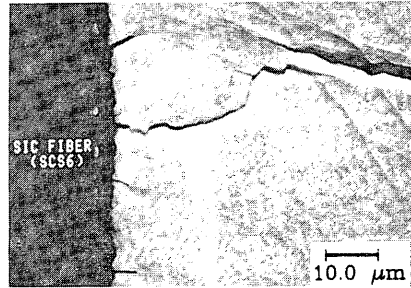
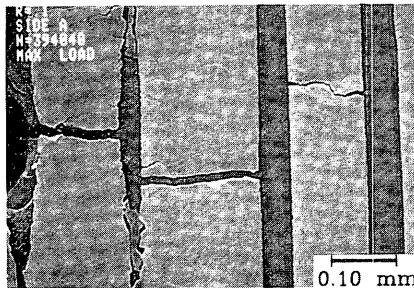
The capabilities of the loading stage allow the researcher to obtain both quantitative and qualitative micromechanical behavior data required to understand and model the fatigue or static behavior of composites. This information includes actually observing the active fatigue crack growth damage processes and their dependence on the individual composite constituents; identifying the constituent most susceptible to damage as well as the stress required for it to fail; and quantifying the

crack driving force by measuring such variables as the crack tip strain fields and crack bridging by the fibers. The loading stage is also used to quantify the extent of sustained composite damage by measuring the amount of debonding and the change in the compliance due to internal composite damage.

The loading stage is currently being used to study fatigue crack growth behavior of an SiC-fiber-reinforced Ti-15-3 matrix composite. In this composite the interface region and in particular the carbon coating surrounding the fiber was found to be the constituent most susceptible to fatigue damage. The bridging of the crack wake by the fibers substantially reduced the crack propagation rates. The measured crack tip strain fields are currently being used to model the actual crack driving force.

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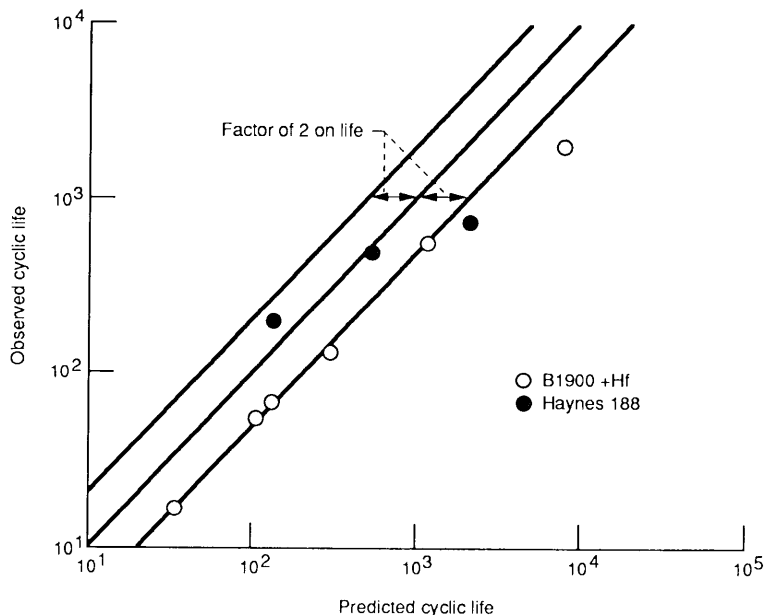


Scanning electron micrographs of metal matrix composite

### Thermal Fatigue Life Prediction: A New Approach

NASA Lewis has proposed a new approach for predicting thermal fatigue crack-initiation lives in high-temperature structural components. The approach represents the culmination of several recent advances in describing high-temperature material behavior. These include the bithermal fatigue concept for characterizing the cyclic failure resistance of materials to nonisothermal loadings; advanced nonlinear cyclic constitutive models for nonisothermal cycling conditions; and the total-strain version of the Strainrange Partitioning (SRP) method for creep-fatigue interaction. Of particular significance is the applicability of the approach to the highly practical low-strain, long-life regime for which inelastic strains are present but are too small to be determined accurately.

With the bithermal fatigue concept an alloy's nonisothermal fatigue failure characteristics can be characterized simply with a minimum of testing. Using advanced nonlinear viscoplastic constitutive models (such as those by Robinson, Freed, Walker, and Bodner) permits interpolation and extrapolation to any wave shape, frequency, dwell time, and temperature range of concern. Using the total-strain version of SRP permits casting the approach in terms of total strains, thus providing a failure criterion based upon the primary driving variable in thermal fatigue problems—the total mechanical strain range. The approach is just now being verified in its entirety, although individual elements have been verified earlier. A limited data base for verification purposes has been generated for two high-temperature aerospace structural alloys (cast B1900 + Hf and wrought



*Verification of new thermal fatigue life prediction model*

Haynes 188). The method represents a rational, physically consistent approach to predicting thermal fatigue life. All of the variables known to affect thermal fatigue life can be handled directly by this approach. The necessary data base depends upon the degree of complexity required in solving the thermal fatigue problem at hand. The required data bases are, however, well defined. The approach represents a significant advance in our ability to describe and predict thermal fatigue crack initiation lives of high-temperature alloys.

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## Computer Program for Predicting High-Temperature Fatigue Life

Under contract with NASA Lewis, Pratt & Whitney Aircraft is developing a high-temperature-fatigue, crack-initiation life prediction model for use in the aerospace propulsion industry. Fatigue crack initiation life is defined as the development of a surface fatigue crack 0.030 in. long. The model, cyclic damage accumulation (CDA), has been developed to deal with the numerous and complex durability problems that face designers of hot-section components in advanced propulsion systems. Recently, the model has been implemented into a research computer program that can be run with equal ease on a personal computer, a workstation, or a main-frame. Model selection was based upon practical engineering considerations that dictated a minimum data base and ease of material testing and evaluation of model constants—even to the point of sacrificing absolute accuracy. The governing concept was that much of the inaccuracy can be calibrated out of the problem when service history results are compared with model predictions.

An important engineering feature of the model is the manner in which all behavior is considered relative to a single fixed reference condition of temperature, loading rate, loading level, environment, etc. Thus, only limited data are required to calibrate the model for a new material. The basic CDA creep-fatigue model has been developed in a modular fashion, permitting users to select only those aspects of a problem that are pertinent. Modules have been prepared to deal with mean stresses, multi-axiality, thermal fatigue, coatings, environmental interactions including oxidation, and cumulative damage.

The outputs of finite element structural analyses are used as direct input to the CDA life prediction model.

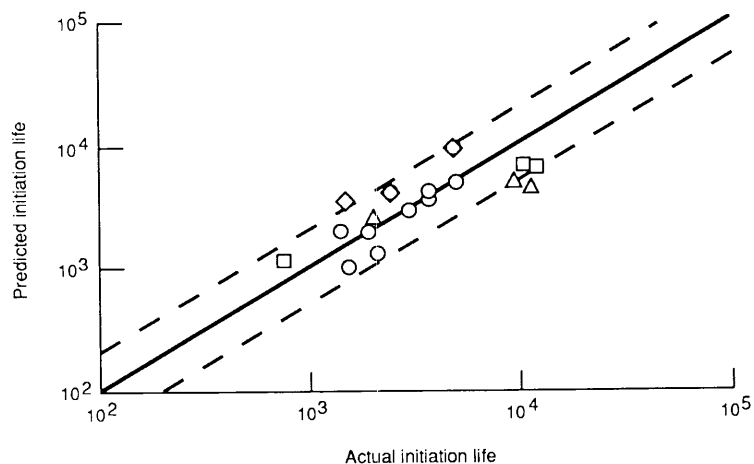
Copies of the CDA computer program have been distributed to the 30 organizations that participated in the users workshop held recently at NASA Lewis. Feedback from these users will be incorporated into the model before it is scheduled for delivery to COSMIC for distribution to the general public. To date, the model has been calibrated to accept the behavior of two high-temperature nickel-base superalloys, cast B1900 + Hf and forged Inconel 718. CDA workshop participants will be evaluating the model for materials of more direct

individual interest. A follow-up workshop is being considered for 1990 to share the experiences of using the new program.

The CDA model will be the first generalized high-temperature, creep-fatigue, crack-initiation life prediction method to be made available in a computer code format for public consumption. Additional high-temperature models are being prepared for similar release within the next year.

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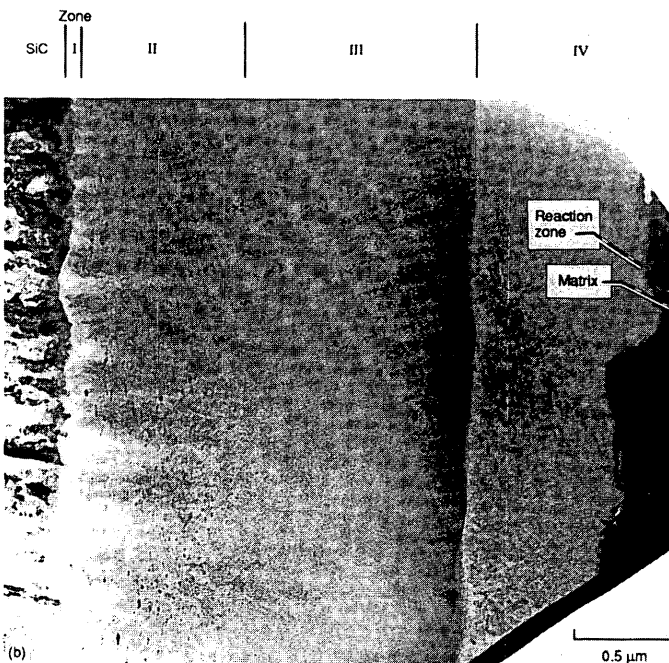
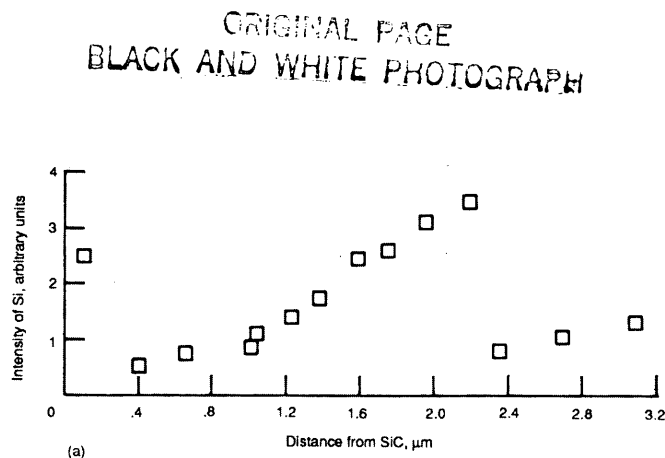
*Verification of CDA model for thermomechanical fatigue of cast B1900 + Hf.*

### Microstructural Characterization of SiC-Reinforced Titanium Composite

In order to better understand fatigue processes and thus develop accurate life prediction models for composite materials, researchers at NASA Lewis are investigating an SiC-reinforced Ti-15V-3Cr-3Sn-3Al material. As part of this effort microstructural details of the fiber, the interface region, and the matrix were examined. Aging studies were performed to gain insight into the behavior of the matrix material, including its microstructural stability at elevated temperatures.

Techniques were developed to produce thin foils of the composite material that were transparent to an electron beam. Examination of these foils by transmission electron microscopy yielded information on the fiber and the fiber-matrix interface. These analyses showed the SiC fiber to consist primarily of elongated grains. On the outer surface of the fiber a 3- $\mu\text{m}$ -thick coating, which consisted of carbon and silicon, was evident. X-ray elemental analysis indicated that the silicon content within this coating varied as a function of position, being highest near the fiber and at 1  $\mu\text{m}$  from the matrix. The coating reacted with the matrix during consolidation to form a narrow reaction zone, consisting of small particles of  $\text{TiC}$  and  $\text{Ti}_5\text{Si}_3$ .

Detailed heat treatment studies were performed to investigate the aging behavior of the in-situ composite matrix. The matrix consisted of a  $\beta$ -Ti phase hardened with precipitates of  $\alpha$ -Ti. The matrix could be aged to produce various sizes and distributions of the precipitate. Heat treatment at 450 °C produced maximum hardness in the



Elemental analyses for silicon content in carbon-rich coating:  
(a) silicon content, (b) bright-field micrograph

composite matrix for an aging time of 24 hours. Aging temperatures above or below 450 °C yielded overaged or underaged conditions, respectively.

This work has shown that heat treating the composite will affect the matrix microstructure. Exposure of the composite to elevated temperatures, during testing or in service,

will likewise change the behavior of the matrix. Changes in the matrix microstructure could affect the mechanical properties of the composite, a point that will be addressed in future research.

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# Internal Computational Fluid Mechanics

## Turbomachinery Flow Modeling

A mathematical analysis has yielded a set of equations governing the conceptual flow model currently used to design turbomachinery blading. These equations govern the time-averaged flow state within a typical passage of a blade row embedded in a multistage configuration. This mathematical exercise has been transformed into a number of computer simulation models and has aided in the formulation of two turbomachinery research programs. The first research program is focused on advancing our understanding of the flow phenomena that affect the performance and life of multistage compressor blading. This research effort integrates computational fluid dynamics, flow modeling, and experimental fluid mechanics to develop flow models that designers can apply to advanced blading. Both university and industrial researchers have been and will continue to be active participants in this program.

The second research program will examine the control of secondary flow structures within low-aspect-ratio multistage turbines. A viscous multistage code developed at NASA Lewis will be used in this study. This code has qualitatively reproduced the time-averaged effect of the secondary vorticity field generated within a turbine rotor on the downstream vane. The secondary flowfield that can develop within a turbine rotor passage is illustrated in the accompanying figure. The flow is from right to left. Colored fluid particles released along the pressure surface are seen to migrate toward both the hub and shroud endwalls. As they approach these walls, they merge into the nonaxisymmetric secondary flowfield, which the

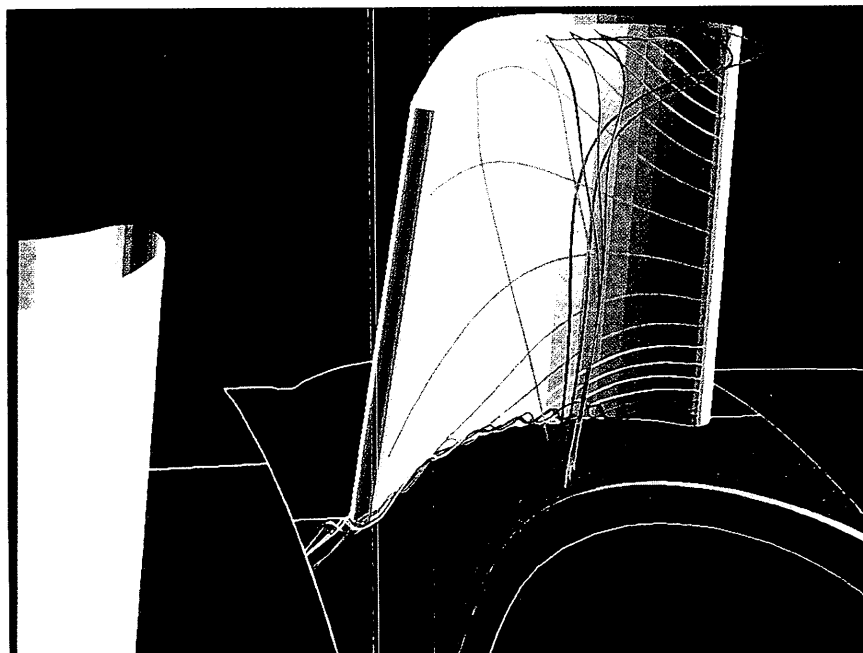
downstream vane on the left of the figure senses as an unsteady inlet distortion. The control of this distorted inflow can lead to significant improvements in the performance of turbine vanes, and hence improvement in the performance and life of turbines.

In anticipation of this program a new grid generation code has been developed for the multistage viscous code. This grid code provides considerable control over the placement and orthogonality of grid points near solid surfaces and in the

wake region. The code is interactive and fast and is implemented on a workstation. A number of requests have been received from industry for copies of the code. Simulations performed with these grids have converged faster and provided a greater resolution of the viscous layers than previous simulations using a simple sheared grid.

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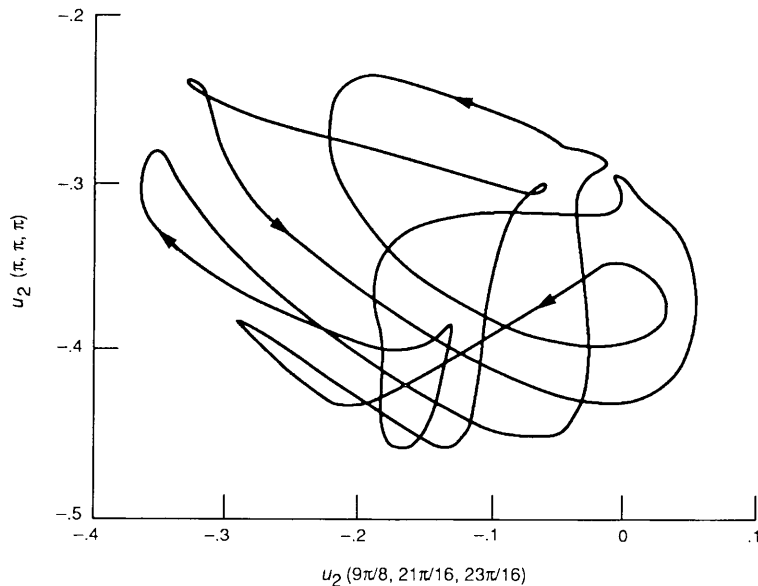


*Secondary flowfield in turbine rotor passage*

## Characterization of Turbulence

NASA Lewis' work on the characterization of fluid turbulence is continuing. We have identified turbulent flows as flows in which initially neighboring solutions, on the average, separate exponentially with time. That is, turbulent flows are chaotic. Another characteristic of turbulence is that it is aperiodic or nonperiodic in time. In order to better understand what turbulence is and is not, in that respect, we contrasted it with periodic flows; we were able to obtain numerically some time-periodic solutions of the Navier-Stokes equations at Reynolds numbers lower than those for which turbulent flow can be sustained.

First, we obtained a simple periodic flow in which the orbit in phase space has a simple shape. Then by increasing the Reynolds number slightly, we obtained the much more complicated periodic flow shown in the accompanying figure, where a velocity component at one point in the flow is plotted against a component at another point. Because of the flow's complexity one might at first glance mistake it for a turbulent or chaotic flow. However, the flow is definitely periodic, since it traces the same curve over and over. The flow appears to have an exceptionally good memory in being able to do that. By way of contrast, if the flow were turbulent, the curve would not repeat, but the region occupied by the trajectory would continue to get blacker as the running time increased.



*Complex periodic flow*

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## Fundamental Properties of Solids and Interfaces

Current theoretical research into the fundamental properties of solids and interfaces involves the extension of universality in binding energy relations, the equation of state for solids, and the energetic and electronic properties of defects in solids (e.g., grain boundaries). Progress has been made in discovering a universal equation of state for Van der Waals, ionic, covalent, and metallicly bonded solids. These results have been applied to predicting the isothermal temperature dependence of the bulk modulus and its derivatives and the thermal expansion for all classes of solids. Also, the relationships between all the most widely used heuristic equations of state have been established. Some preliminary work is being performed in examining phase changes. The grain boundary studies involve implementing and improving on some new techniques—the equivalent crystal theory and the embedded atom method—for calculating energies, including the many-body interactions. The equivalent crystal theory is presently being used to study adhesion, shear, and the atomic force microscope. The embedded atom method is being used to improve the Frenkel model for shear. Universality is being generalized to cases with charge transfer for diatomics, with the hope that it can be applied to solids, extending the techniques to ceramics and metal-ceramic interfaces. Fully quantum mechanical calculations by the linear muffin-tin orbital method are being used to examine the band structure of photovoltaic materials and the equations of state for ionic solids.

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## Enhancement of Turbulent Mixing

Considerable technological interest exists in using small-amplitude excitation for controlling mixing in free shear layers. External forcing produces spatially growing instability waves that are initially governed by linear dynamics if the excitation amplitude is sufficiently small. While the instability wave amplitude continues to increase in the downstream direction, its local growth rate must ultimately decrease owing to viscous spreading of the mean shear layer and nonlinear effects. Nonlinear effects first become important in the critical layer. A composite expansion technique is used to obtain a solution that accounts for both shear-layer spreading and nonlinear critical-layer effects.

For the two-dimensional incompressible case the flow in the critical layer is governed by a nonlinear vorticity equation, and the instability-wave amplitude is completely controlled by the nonlinear dynamics of the critical layer. The numerical results show that, because of the continued roll-up of the vorticity, even weak viscous effects lead to a conversion of the initial exponential growth to an algebraic one and to the emergence of a quasi-equilibrium critical layer. The asymptotic structure of this stage has been obtained and used to infer the scaling for the next stage of evolution in which the instability-wave growth is simultaneously affected by mean-flow-divergence and nonlinear critical-layer effects and is eventually converted to decay. This final stage has been incorporated into the composite solution, accounting for both mean-flow spreading and nonlinear



effects. Comparisons with available experimental results are presently being carried out.

In supersonic shear layers the most rapidly growing instability wave can be three dimensional, and the analysis has been extended to incorporate such waves. Three-dimensional effects dramatically change the nonlinear behavior, which now enters at much smaller amplitudes than in the two-dimensional case. The numerical results show that under certain conditions the instability-wave amplitude becomes algebraically singular at a finite downstream position, showing that the motion is governed by the full three-dimensional Euler equations in the vicinity and downstream of that position.

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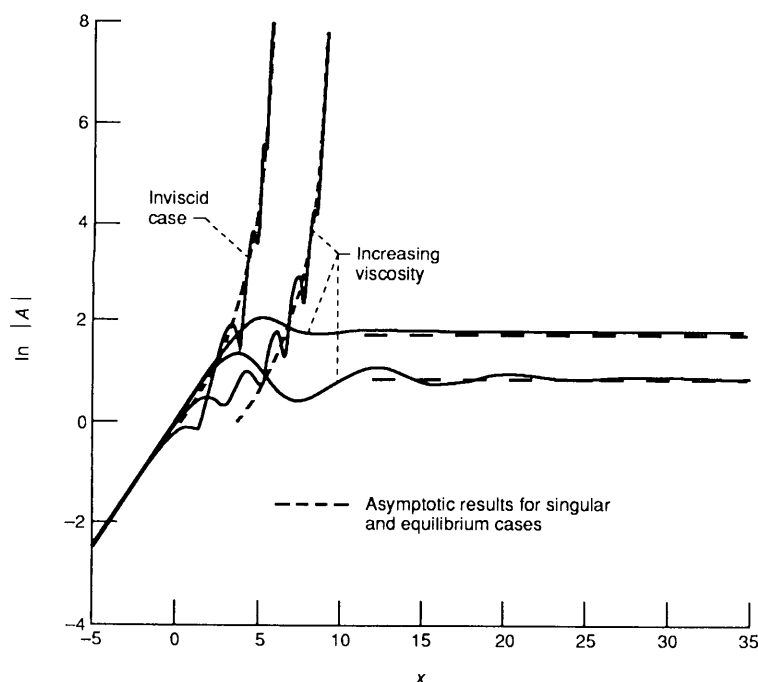
Headquarters program office: OAST

## Boundary Layer Transition

Experimentalists usually study the boundary layer transition problem by artificially exciting their flows with relatively two-dimensional, small-amplitude, single-frequency excitation devices, such as a vibrating ribbon or an acoustic speaker. The initial disturbances in such experiments usually have harmonic time dependence, are well described by linear stability theory, and at the low Mach numbers at which most experiments have been carried out are nearly two dimensional. This two-dimensional linear behavior can persist over extremely long streamwise distances when the excitation levels are sufficiently small, but the disturbance usually becomes three dimensional at sufficiently large downstream distances. A number of transition analyses that closely correspond to such experimental configurations have been carried out.

Since the linear phenomena seem to be more or less well in hand, the analyses concentrated on the nonlinear stage of development. The first nonlinear stage in the subsonic flow excitation experiments is associated with the appearance of a more or less periodic spanwise structure in the flow (peak valley splitting, etc.). The relevant nonlinear solutions that describe this phenomenon should represent the natural downstream continuation of the linear (weakly nonparallel) solutions that hold farther upstream.

The spanwise structures are probably due to a resonant triad interaction between a pair of oblique subharmonic modes and a basic fundamental two-dimensional mode. A completely rational asymptotic analysis of this phenomenon has



*Three-dimensional instability-wave amplitude versus streamwise distance for a compressible shear layer*

been carried out for the main unstable region. It shows that the nonlinearity is confined to a thin sublayer and occurs at extremely small instability-wave amplitudes and that only extremely large oblique modes backreact on the two-dimensional mode.

The nonlinear dynamics can be quite different at supersonic speeds. The most rapidly growing linear mode can then be an oblique wave in the appropriate Mach number range, and it might be difficult to generate the two-dimensional mode experimentally. Two possibilities exist: One can generate a single oblique mode by placing the excitation device at the appropriate oblique angle to the flow (corresponding to the direction of maximum instability-wave growth), or one can produce a pair of oblique waves with the same streamwise wave number and frequency but equal and opposite spanwise wave numbers (corresponding to a standing wave in the spanwise direction) by placing the excitation device perpendicular to the flow. In the latter case the two oblique modes can interact nonlinearly in their mutual critical layer, causing the nonlinearity to come into play at extremely small instability-wave amplitudes. The critical-layer nonlinearity is weak, with the result that the instability-wave amplitude can be determined from a single so-called amplitude or evolution equation as in classical, weakly nonlinear theory. However, this equation differs from that of classical theory in that it involves upstream history effects and is therefore an integro-differential equation rather than an ordinary differential equation. In the inviscid limit the solution to this equation always ends in a singularity at a finite downstream position—

indicating an explosive growth of the instability wave there.

At higher Mach numbers the so-called second mode has the largest linear growth rate, which always occurs at zero obliqueness. Here the temperature fluctuations, which (on linear theory) become infinite algebraically fast in the critical layer, cause the critical-layer nonlinearity to again occur at extremely small instability-wave amplitudes. But the nonlinearity is again weak, so that the amplitude can again be determined from a single amplitude equation similar to the equation for the oblique mode case. The solution to this equation is again found to end in a singularity at a finite downstream position when the appropriate scaled viscous parameter is sufficiently small. However, there is also a certain range of parameters in which the singularity is bypassed when this viscous parameter exceeds a certain finite value—in which case the solution just goes to a finite-amplitude equilibrium state farther downstream.

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## Instrumentation & Controls

### R&D 100

#### Vector-Scanning Data Reduction for Pulsed-Laser Velocimetry

Pulsed-laser velocimetry (PLV) provides a nonintrusive, instantaneous, two-dimensional planar velocity record of a particle-seeded flowfield. Instantaneous recording of a flow across an extended planar region permits the study of transient flows and reduces the data acquisition time. Current PLV processing techniques require tedious data analysis procedures and several hours of processing time, yet give ambiguous velocity vector direction information. The vector-scanning processing technique is a personal-computer-based system that provides unambiguous, simple, fast, and reasonably accurate (2 to 20 percent) velocity vector estimates from PLV data.

In the vector-scanning technique the flowfield under study is illuminated by a laser light sheet. A low-light-level camera, oriented perpendicular to the light sheet, records the particle positions. A sequence of successive images is digitized at video rates by a frame-grabber board. The sequence of digital images is processed to generate a single image that contains the time history information of all the particles recorded in the sequence. A particle's time history information is used to track the particle over the sequence of images. A particle's velocity is calculated by determining the total displacement over the series of frames and using the interframe acquisition time. Velocity vectors are only determined where particles are recorded in the flowfield. All of the data acquisition and processing is performed on a 25-MHz 386-based personal computer. The total processing time from data acquisition to the generation of

a two-dimensional velocity vector map is less than 2 min.

Vector scanning has been used to reduce preliminary low-velocity fluid flow data from the prototype setup of a surface-tension-driven convection experiment scheduled for a space shuttle flight in 1992. In the experiment the surface of a fluid contained in a cylindrical reservoir is heated with a CO<sub>2</sub> laser beam, which drives a circularly symmetric counterrotating vortical flow. The laser light sheet illuminates a cross section of the vortical flow pattern. The data have been reduced both directly from the low-light-level camera and from a video tape. Smoothing the data produces a regular grid of velocity vectors from the randomly sampled flowfield. Only low-speed flows (<20 mm/sec) have been processed with vector scanning. Work is under way to extend the

velocity measurement capability into the 10- to 100-mm/sec velocity range.

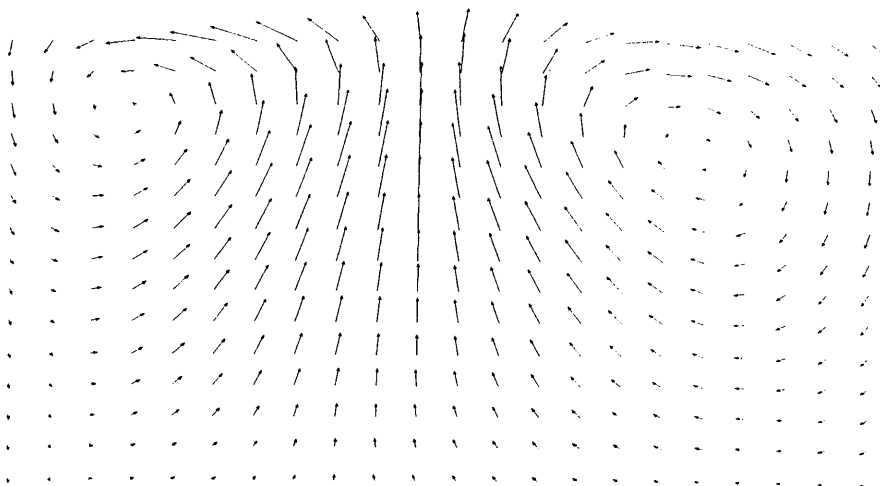
The vector-scanning data reduction technique was developed in house under the Director's discretionary fund. The vector-scanning technique is also a recipient of a 1989 R&D 100 award from Research & Development magazine.

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*Measured vortical flow pattern from prototype setup of surface-driven convection experiment*

## Two-Dimensional, Laser-Based Strain Measurement System

The development of advanced materials suitable for use in extremely high-temperature propulsion applications extends the requirements on instrumentation used to characterize these materials and to verify models of component parts. NASA Lewis has developed the capability to make two-dimensional optical strain measurements on high-temperature test specimens in a laboratory environment. This effort is a part of the Structural Integrity and Durability of Reusable Space Propulsion Systems Program.

This system makes two-dimensional strain measurements by rotating the sensitive axis of the optical instrument. Three components of surface strain can be measured automatically; from these components the first and second principal strains are calculated. The system has demonstrated one-dimensional and two-dimensional strain measurements at temperatures above 750 °C. No upper temperature limit of the technique has been observed during the tests. Some of the features of the technique include noncontact measurements, automatic cancellation of rigid-body motion, no surface preparation, and near-real-time results. The system also features a gage length of less than 1 mm and a resolution of 15 microstrains. The system is controlled by a high-speed microcomputer with hardware processing capabilities.

The system is based on a one-dimensional speckle-shift technique. Laser speckle is a phase effect that occurs when spatially coherent light interacts with an optically rough surface. The speckle-shift technique makes use of the linear relationship

between surface strain and the differential shift of laser speckle patterns in the diffraction plane. Since speckle is generated by any diffusely reflecting surface, no specimen preparation is needed to obtain a good signal. Speckle shifts are measured from a laser beam incident on a test specimen at 30° from the surface normal. By also measuring the speckle shifts from a beam incident at an equal and opposite angle, potential errors due to rigid-body motions are automatically eliminated.

Future efforts will include reading two-dimensional speckle patterns with an area array camera and interfacing a digital signal processor with the computer. This will extend the range of tolerable rigid-body motion and

reduce the processing time to the point that true real-time measurements can be made.

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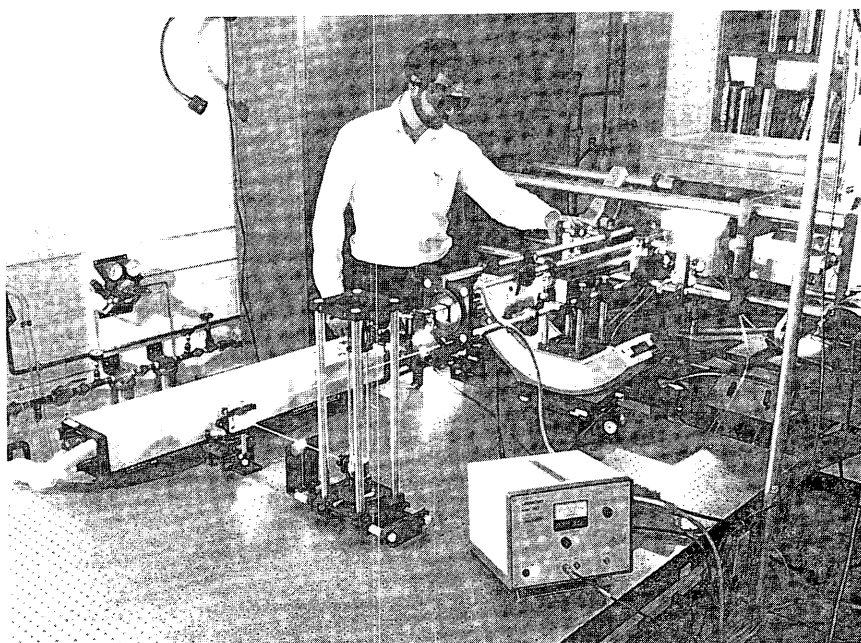
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*Two-dimensional, laser-based strain measurement system*

### Fiber-Optic, Alternating-Current Sensor

As part of the Space Power Program, NASA requires sensors that perform reliably in adverse environments, including temperature extremes, vibration, and electromagnetic interference. Occasionally, static discharges in satellites have resulted in loss of control. NASA Lewis and the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) at Boulder, Colorado, are jointly developing a robust fiber-optic, alternating-current sensor that can be used in remote locations in aircraft and spacecraft without electromagnetic interference. The sensor is especially broadbanded so that it can be used with both low-frequency (60 Hz) and high-frequency (20 kHz) aerospace electric power systems.

Polarized light from a laser diode is sent along an optical fiber into a multiturn optical fiber coil and then is returned to a detection system via another optical fiber. A conductor carrying alternating electric current runs through the center of the coil, and the magnetic field caused by the current rotates the polarized light as it propagates through the coil. The output polarization is detected, resulting in an output directly proportional to the electric current in the conductor.

NASA determined the typical operating conditions for aerospace current sensors and also specified performance requirements. NIST developed special methods of annealing the optical fibers used in the pickup coil in order to reduce sensitivity to changes in sensor operating temperature. Extra attention was given to methods that made the sensor more robust. Care was also taken to make the sensor changeable and versatile so that it would be a good experimental tool. NIST will soon complete construction of an operating sensor system that NASA will then submit to temperature and vibration testing. Follow-on work will include advanced development of a fiber-optic voltage sensor.

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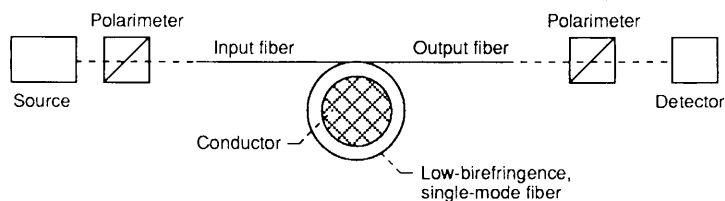
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### Interfacing Laboratory Instruments to Multiuser, Virtual-Memory Computers

Computers based on "virtual memory" multiuser architecture have recently become economically available to medium-size research groups. Although these new computers offer advantages to the experimenter, acceptance has sometimes been limited. Many researchers are accustomed to a dedicated computer running a single-user operating and data acquisition system. When there are several experimenters in a research group, the advantage of a multiuser system becomes obvious. The resources a computer provides can be shared among the users at a much lower cost than that of maintaining a separate dedicated computer and peripherals for each project. Software routines for instrument control and data acquisition as well as data bases are sharable resources. Expensive hardware resources such as array processors, image processors, terminals, printers, and color plotters can also be shared.

There are difficulties in assembling the hardware and software facilities required for a research-oriented multiuser system. The single-user operating system typically uses built-in commands for easy instrument communication and other functions well suited for the experimenter's needs. A multiuser computer's input-output capabilities are more powerful but not as simple to understand. The user is left with the responsibility for bridging the gap between the capabilities provided and his or her particular needs for data acquisition and communication with devices.



*Simple polarimetric optical fiber current sensor*

Work has been completed to provide the information required for setting up a multiuser computer system that will meet the needs of a medium-size research group. The basic computer system and its components have been described. Specific examples of instrument control and data acquisition with a multiuser system have been highlighted for use in both Basic and Fortran programming. A collection of high- and low-level subroutines for computer control of instruments is available.

#### Bibliography

Generazio, E.R.; Stang, D.B.; and Roth, D.J.: Interfacing Laboratory Instruments to Multiuser, Virtual Memory Computers. NASA TM-4106, 1989.

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#### Transient Finite Element Analysis on Transputer System

Many large-scale computer simulations involve such an enormous number of computations that they are too time consuming for even today's supercomputers. To achieve large increases in computational speed, researchers have focused on parallel-processing computers. Parallel-processing computers are composed of two or more interconnected processors. For parallel computations a task is divided into subtasks that are performed independently on separate processors.

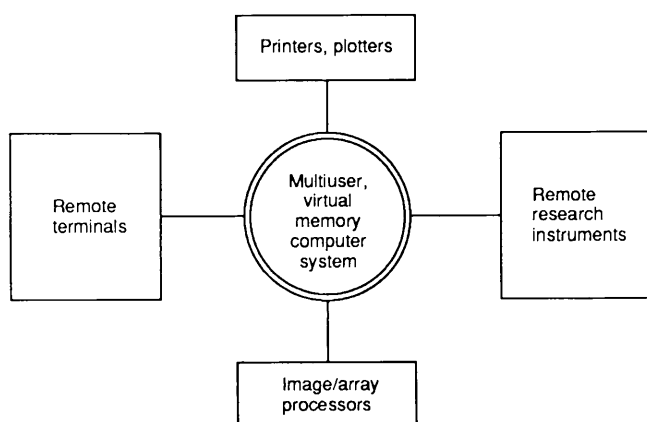
This study used a parallel-processing computer for analyzing dynamic finite element problems. Direct time integration methods are most useful for analyzing dynamic problems because they are applicable to nonlinear structural problems. Some

examples of nonlinear problems are structures with large displacements and those composed of a nonlinear material. With direct methods the time period of interest is split into small steps and the solution is computed at each time step. In some nonlinear problems a new system of equations must be solved at every step. The solution of such problems can be too time consuming if many time steps are needed or if a large system of equations must be solved. For example, three-dimensional finite element problems can have several hundred thousand equations. For this reason parallel processing is being investigated as a means of speeding up this type of analysis.

In this study the central difference method was chosen for the time integration rule. Since this is an explicit method, the displacements at different nodes of the finite element mesh can be computed independently of each other over a time step. This allows the finite element problem to be partitioned into subproblems that are solved on different processors. A system of transputer microprocessors was used for the computations.

A one-dimensional bar problem was analyzed by using a parallel algorithm. The bar was divided into subproblems, which were assigned to different processors. Information was exchanged between the processors after every time step. Doubling the number of processors decreased the computing time by nearly half.

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*Multiuser computer system for nondestructive evaluation research*

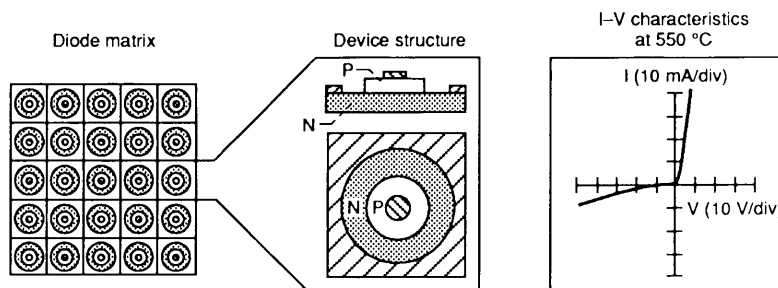
## Electronics

### High-Temperature Silicon Carbide Diode

NASA Lewis is developing a new family of semiconductor devices based on silicon carbide (SiC). The goal is sensors and electronic devices for operation at 600 °C (and beyond) in aerospace propulsion and power applications. Large-area  $\beta$ -SiC single-crystal films are currently being grown on silicon substrates at Lewis by a chemical vapor deposition (CVD) process. These films are actually large, thin crystals of the cubic form ( $\beta$ ) of SiC. They have been used to fabricate a p-n grown-junction diode that has been operated to 550 °C.

The p-n junctions were produced by first growing a 10- $\mu$ m-thick n-type  $\beta$ -SiC film and then growing an additional 0.5- $\mu$ m-thick  $\beta$ -SiC film with diborane added to the process gases. Boron from the diborane was incorporated into the growing SiC film to produce p-type material. An array of diode mesa structures was then formed by reactive ion etching. Ohmic contacts, aluminum/silicon to the p type and gold/tantalum to the n type, were then applied by sputter deposition.

The current-voltage (I-V) curve in the accompanying figure demonstrates the performance of one of the  $\beta$ -SiC diodes at 550 °C. The function of a diode is to allow current to pass in one direction (the forward direction) but not in the opposite (reverse) direction. Hence, an ideal I-V curve would be nearly vertical in the forward direction and nearly horizontal in the reverse direction. The I-V curve for this diode at 550 °C, although not ideal, does demonstrate good current rectification. The result is significant for several reasons. First, 550 °C is the highest



*Matrix, device structure, and performance at 550 °C of high-temperature silicon carbide diode*

operating temperature ever reported for a  $\beta$ -SiC diode; second, its leakage current is significantly less than any other previously reported  $\beta$ -SiC grown-junction diode at temperatures above 400 °C; and finally, it demonstrates that good device performance can be achieved in spite of the high density of crystal faults in the film. Future work will be directed toward reducing reverse leakage currents and the forward voltage drop at high currents.

Since the p-n junction is a basic component in many semiconductor devices, it is expected that this result will be important in the development of high-temperature SiC semiconductor technology. Applications in both propulsion and power systems will benefit from this technology.

#### Bibliography

Powell, J.A.; Matus, L.G.; and Kuczmarski, M.A.: Growth and Characterization of Cubic SiC Single-Crystal Films on Si. *J. Electrochem. Soc.*, vol. 134, no. 6, June 1987, pp. 1558-1565.

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## High-Efficiency Traveling-Wave-Tube Amplifiers for Deep Space Communications

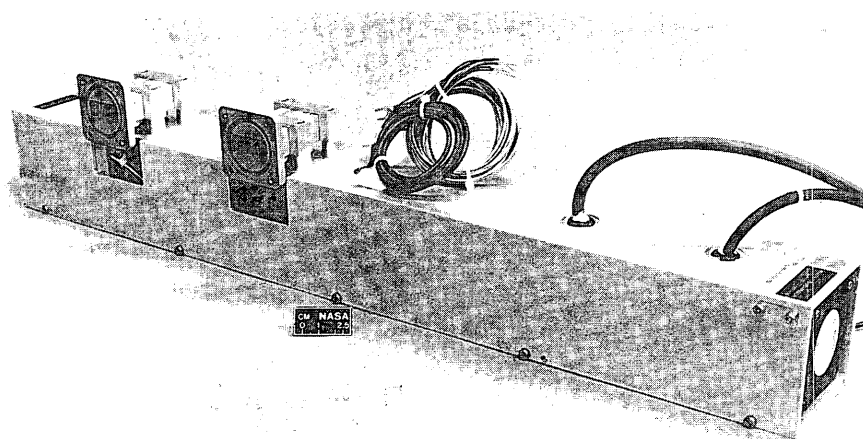
NASA Lewis is providing the technology needed for high-efficiency, millimeter-wave communications amplifiers for future NASA missions in deep space. A 20-W X-band traveling-wave tube (TWT) with a high-efficiency, slow-wave circuit has been designed by Lewis personnel and fabricated by Watkins-Johnson. The circuit developed for this TWT was adopted for use on the one that will be flown on the Mars Observer, exceeding the mission requirements for efficiency.

Efficiency enhancement technologies apply throughout the TWT and include improving the interaction between the electron beam and the electromagnetic wave, recovering the energy in the spent electron beam, improving electron beam transmission, reducing cathode heater power, and reducing secondary electron emission from collector electrodes. The work involves both computer-aided design and analysis as well as experimental verification.

The next step is to produce an extremely efficient 32-GHz traveling-wave-tube amplifier (TWTA) that produces 7 W of radiofrequency output power with direct-current input to the power supply of only 20 W. Achieving this goal would approximately double the efficiency of 30-GHz TWTA's now available at this power level.

The program objectives were chosen after consultation with the Jet Propulsion Laboratory with a view toward possible application to the Cassini mission to Saturn. The traveling-wave tube is to incorporate an advanced helix interaction section (dynamic velocity taper) design and a high-efficiency multistage depressed collector, as well as a spent-beam refocusing section.

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*High-efficiency traveling-wave tube for deep space*



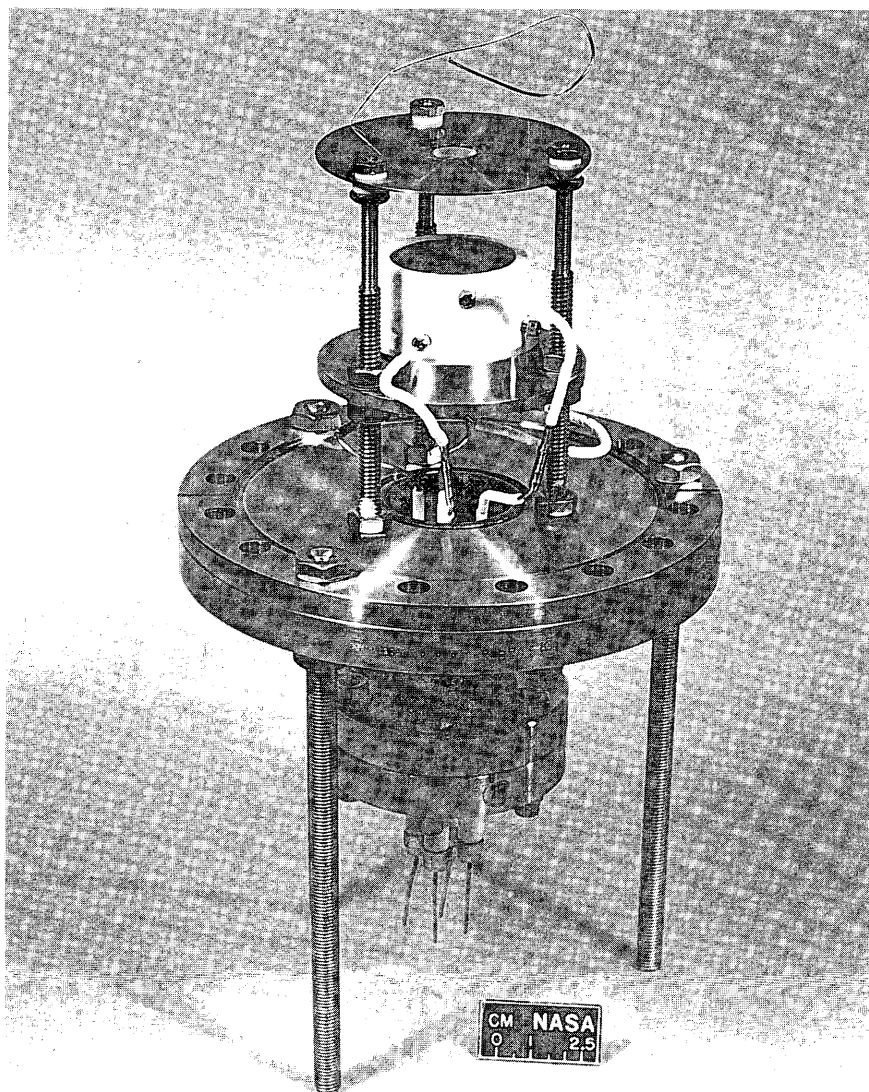
### Miniature Traveling-Wave Tube

NASA Lewis is employing modern microfabrication techniques and computational procedures to develop a new class of miniature millimeter-wave traveling-wave tubes. These tubes will be designed to produce radiofrequency output powers of about 1 W with good efficiency. Typically, when low-power tubes are built, they are inefficient versions of high-power tubes and are similar in size.

A trapezoidal-vane, slow-wave structure was chosen for a 30-GHz miniature tube, and fabrication will commence shortly. The input and output couplers for this tube are still being modified and tested to reduce losses.

The electron beam gun for the miniature tube has been constructed and is awaiting testing. The installation of a new and improved Faraday cup on the beam-testing apparatus and the failure of one of three step indexers is delaying the test. Extensive software for controlling the step indexers and the digital oscilloscope for the electron beam testing apparatus has been written. A program for scanning and measuring the electron beam cross-section characteristics will be used for the test. The vacuum system for testing the completed miniature traveling-wave tube is being constructed.

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*Electron beam gun for miniature traveling-wave tube*

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## Phase-Adjusted Taper for Coupled-Cavity Traveling-Wave Tubes

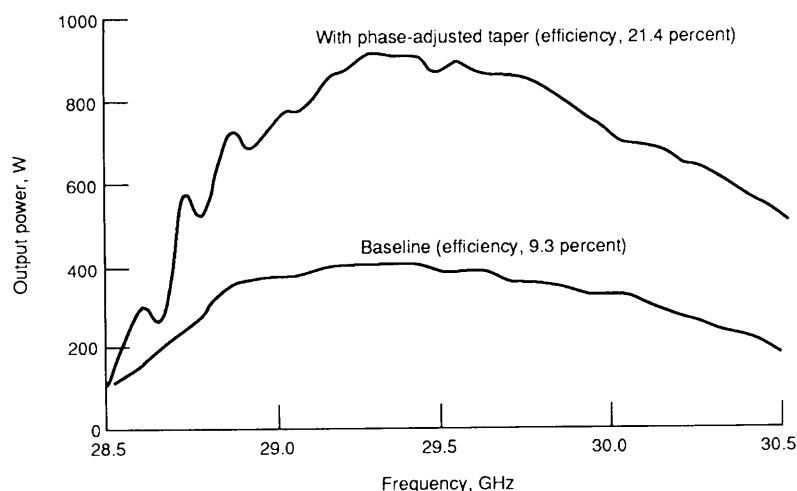
Testing has begun on the fourth Ka-band, coupled-cavity traveling-wave tube (TWT) built under contract by Hughes Aircraft Company. This TWT is the first to employ a phase-adjusted taper recently developed at Lewis to increase efficiency in coupled-cavity TWT's. The first three tubes built under this contract successfully demonstrated the lowest small-signal-gain ripple ever reported for millimeter-wave, coupled-cavity TWT's.

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In the phase-adjusted taper the phase between the radiofrequency wave and the electron bunch is adjusted for optimal energy extraction from the beam. NASA Lewis' coupled-cavity TWT computer code has been programmed to automatically generate the cavity lengths needed to maintain the desired phase relationship. The phase-adjusted taper increases peak output power from 410 W to 920 W. The radio-frequency efficiency is increased by a factor of 2.4, from 9.0 percent to 21.4 percent.



*Experimental output power of coupled-cavity TWT with phase-adjusted taper*

### Submillimeter Backward-Wave Oscillator

The backward-wave oscillator is an electron beam device with potential application as a voltage-tunable local oscillator for spectrometers deployed above the Earth's atmosphere. The goal is to produce an oscillator with a frequency of 1.8 THz ( $1.8 \times 10^{12}$  Hz).

A circuit etched onto a diamond substrate was constructed at Lincoln Laboratory, installed into the backward-wave oscillator, and tested at The University of Utah. Oscillation was immediately observed at beam voltages between 600 and 5000 V, which correspond to frequencies of approximately 135 to 314 GHz. The data indicated that the bandwidth of the circuit is limited by the design voltage of the electron gun (5 kV)

The circuit is a duplicate of the design that was recently fabricated

onto a quartz substrate and that oscillated between 127 and 265 GHz.

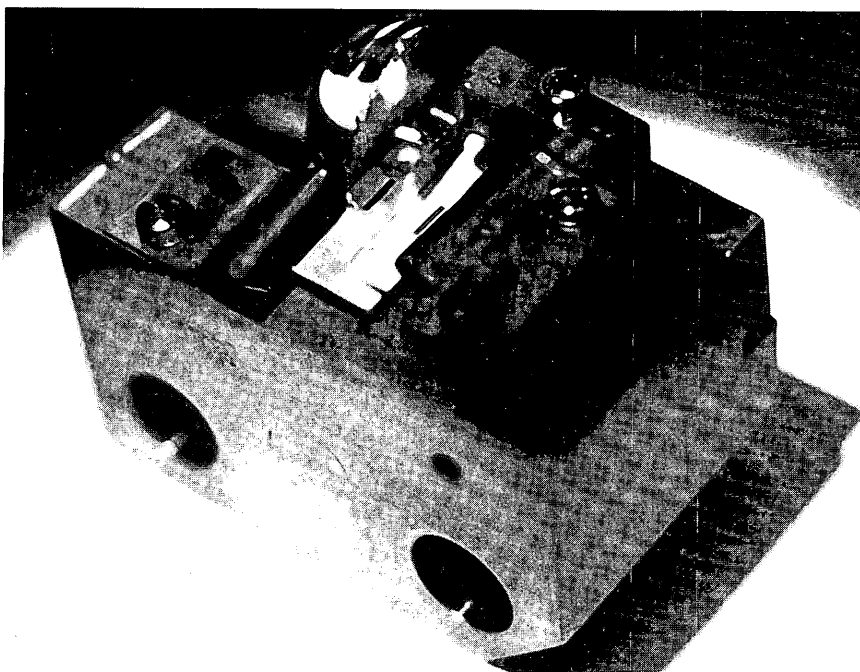
The higher frequencies shown by the diamond circuit are due to the effective lower dielectric loading caused by etching into the substrate.

The broad tuning range of the backward-wave oscillator is made possible by the use of a quasi-optical output coupler, which consists of a horn antenna etched into the plane of the slow-wave circuit and a sapphire lens that focuses the radiation through the vacuum window.

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*Submillimeter backward-wave oscillator with optical output coupler*

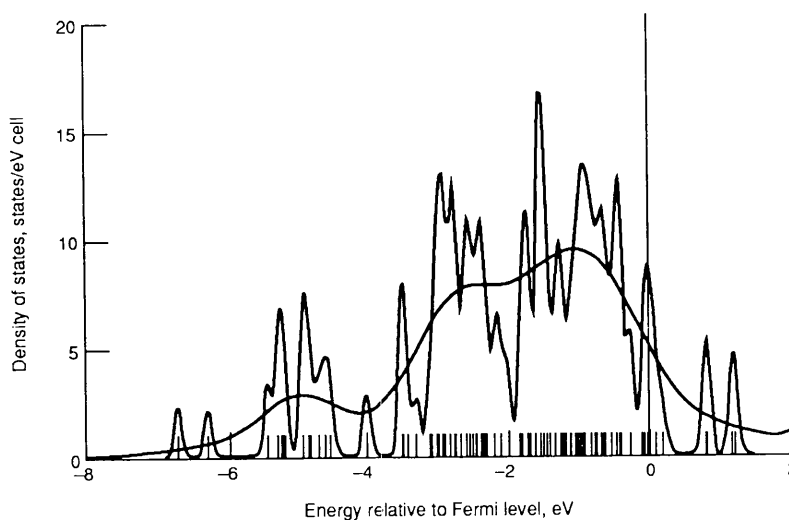
## Theoretical Studies of High-Temperature Superconductors

The electrical structure of the 90 K superconductor YBaCuO has been investigated with cluster calculations based on the self-consistent, relativistic, scattered-wave approach. The validity of the cluster approach has been demonstrated by comparing the results with solid-state calculations and experimental data. The  $\text{Cu}_{3d}$  spin-orbit effects and final state contributions in the photoemission process have been investigated for the first time. After inclusion of the final state effects the accuracy of calculated core-level energies is within 1 to 2 eV, or better than 1 percent. Clusters of the size of a unit cell give a reasonable description of the system, in particular of the surface structure. This will enable the study of surface-related properties and the electronic structure at interfaces.

The accompanying figure shows the computed  $\text{Cu}_{3d}$ - $\text{O}_{2p}$ -related density of electronic states as derived from a  $\text{Y}_2\text{Ba}_2\text{Cu}_{12}\text{O}_{18}$  cluster. The peaked and smooth density distributions were obtained by broadening the indicated cluster energy levels with Gaussians for width parameters of 0.05 and 0.5 eV. The theoretical spectrum shows the two major maxima observed in photoemission experiments, separated by about 2 eV, and additional features at higher and lower binding energies. An analysis of atom-projected partial densities of states shows major copper contributions near the center of the double maximum and oxygen contributions more to its sides—in good agreement with energy-dependent x-ray emission experiments that probe these states separately.

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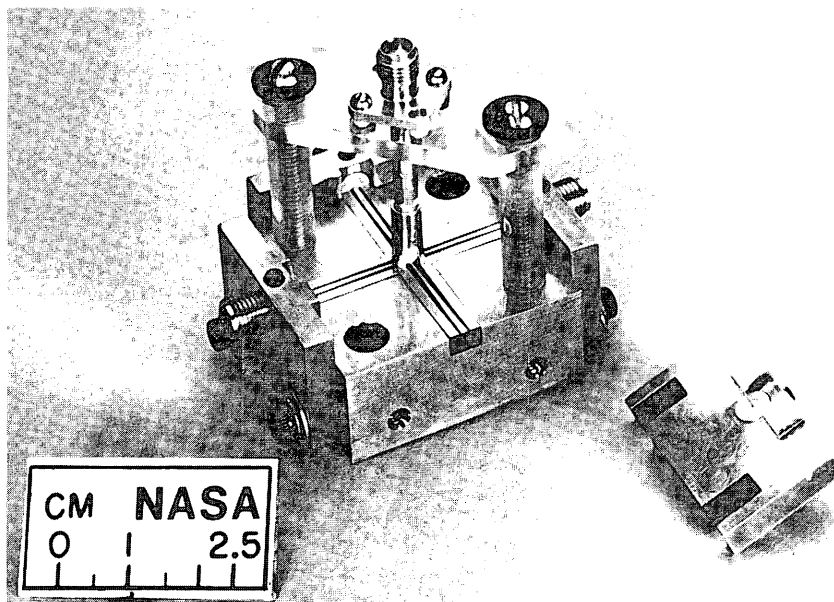
*Computed density of electronic states for YBaCuO*

## Coplanar Waveguide Development

In virtually all monolithic microwave integrated circuits built until now, designers have utilized microstrip technology. Microstrip transmission lines, however, have several disadvantages. They become "lossy" at millimeter wave frequencies; they frequently require "via holes" in the implementation of specific circuitry; and they are often difficult to integrate with other components.

Coplanar waveguides, which include the ground plane on the top surface, avoid most of these difficulties. In addition, implementing millimeter-wave integrated circuits in coplanar waveguides will allow higher levels of integration, will permit all-surface-mount integration, and is ideally suited for on-wafer testing. Taken together, these advantages will yield higher performance and lower cost for millimeter-wave circuits.

During the past year NASA Lewis has designed, fabricated, and tested several components appropriate for space communications or radar systems in coplanar waveguides. One of these is a coaxial-to-coplanar waveguide adapter and a four-way power divider. Testing at Ku-band indicates that the divider exhibits an output power approximately within 0.5 dB of that of an ideal, lossless 1:4 divider. Such a structure is potentially useful in the feed network of an array antenna that uses microwave monolithic integrated circuits. The ongoing program will investigate other coplanar structures at higher frequencies and will develop analytical models that will permit the use of coplanar technology in computer-aided design of microwave- and millimeter-wave circuits.



*Coaxial-to-coplanar waveguide adapter and four-way power divider*

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## High-Critical-Temperature Superconducting Microwave Resonator Circuit

The recent discovery of materials that exhibit electrical superconductivity above liquid-nitrogen temperature (77 K) has prompted renewed interest in many potential applications previously thought to be economically unfeasible. Many of these applications are in the field of microwave or millimeter-wave electronics and include low-loss interconnects for complex systems; small high-quality-factor filters; small, highly efficient millimeter-wave antennas; low-loss, fast, efficient microwave integrated circuits; and the possibility of hybrid superconducting/cooled semiconductor systems.

NASA Lewis is evaluating the usefulness of microwave circuits that use the new high-critical-temperature  $T_c$  superconductors. Over the past year several alternative sources of superconducting films have been developed, substrates appropriate for microwave circuits and compatible with thin films of high- $T_c$  material have been identified, lithographic techniques have been put in place, and methods for carrying out radio-frequency testing at cryogenic temperatures have been developed. Utilizing these capabilities, we have fabricated and tested a microstrip ring resonator at cryogenic temperatures. The circuit was fabricated from a laser-ablated film on a lanthanum aluminate substrate. The lanthanum aluminate was selected because its dielectric constant ( $\sim 20$ ) was suitable for microwave application and its lattice parameters provided a reasonable match to those of the superconductor film being deposited. This is in contrast to the strontium titanate substrate used for

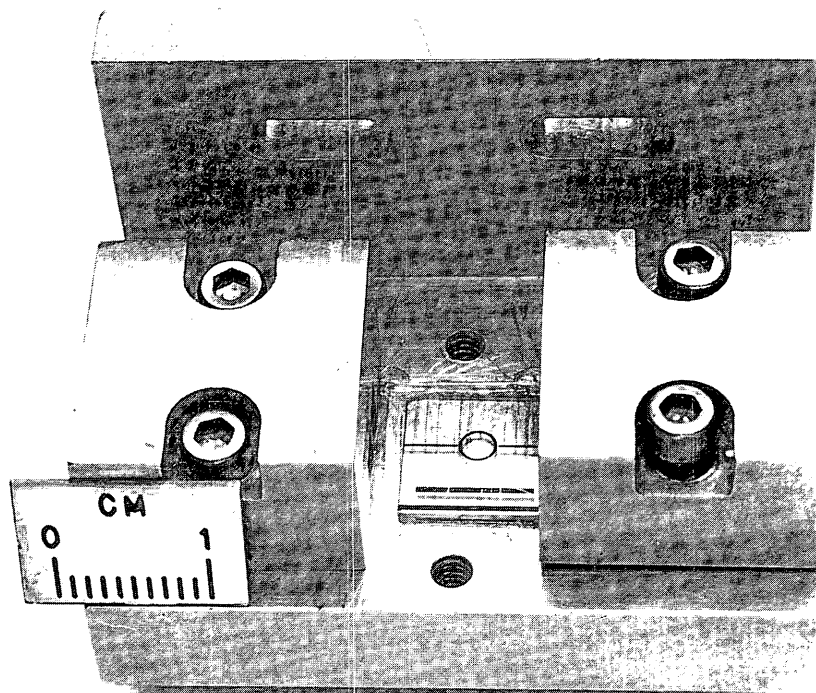
nearly all previous thin-film work. With its dielectric constant of over 200, the strontium titanate is virtually useless for microwave applications.

The resonator utilized a superconducting stripline with a normal metal (gold) groundplane. It was tested over a range of temperatures from 44 K to above the critical temperature of the superconducting film and over a swept range of frequencies near 35 GHz, where it resonated. It was found to exhibit a "Q" approximately twice that of an

identical circuit using a gold conductor at the same temperature. Future work will evaluate other passive circuits such as filters, phase shifters, and power dividers by using several film sources and several transmission line structures. Analytical studies and higher frequency ( $> 100$  GHz) measurements are planned.

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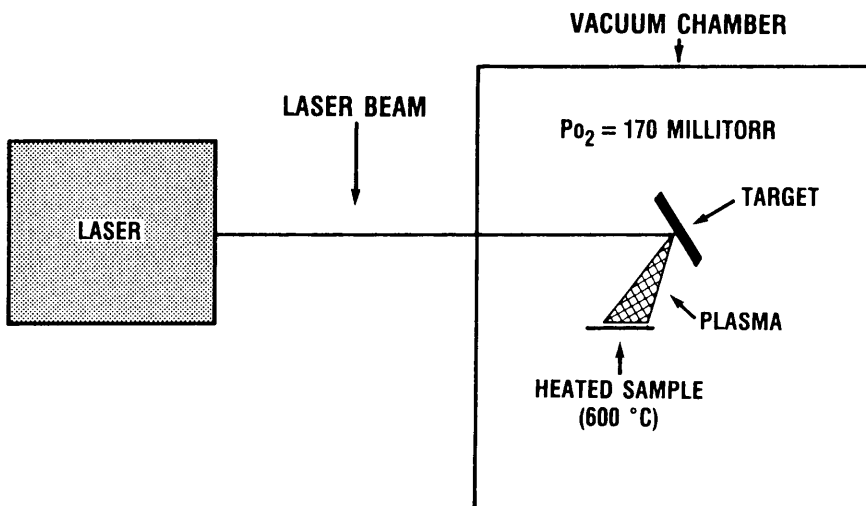
*Superconducting microwave resonator circuit in waveguide test fixture*

### High-Critical-Temperature Superconducting Thin Films

A critical step in evaluating various applications of high-temperature superconductivity is the development of materials appropriate for the specific component or subsystem under consideration. For most microwave or other electronic applications, the requirement is for thin (several micrometers thick) films of material deposited on substrates of low (10 to 30) dielectric constant. In addition, the films must exhibit sufficient (several times  $10^5$  A/cm<sup>2</sup>) current-carrying capability to be useful.

Over the past year NASA Lewis has sponsored film deposition research at a number of universities as well as in house. The university work has resulted in thin films of several materials by means of several deposition techniques. These include sequentially evaporated YBaCuO (Ohio State University), coevaporated YBaCuO (Oberlin College), laser-ablated thallium-based films (University of Nebraska), screen-printed YBaCuO (Case Western Reserve University), and laser-ablated YBaCuO (in house).

Films from each source have been used to fabricate millimeter-wave passive circuits. In particular, the highest quality films appear to be those fabricated in house. These have been oxidized and annealed in situ on a number of substrates, including lanthanum gallate and magnesium oxide, both of which are useful for microwave circuit applications. The films display critical temperatures as high as 89 K and critical currents over  $10^6$  A/cm<sup>2</sup> at 77 K. They have been used in the successful fabrication of simple microwave resonators.



*Laser ablation technique*

Of the films fabricated under university grant, the thallium-based, laser-ablated materials have displayed critical temperatures above 115 K but have not yet been able to achieve the required critical currents. In addition, they have not yet been deposited on microwave-useful substrates. Similarly, YBaCuO films deposited by techniques other than laser ablation have achieved high critical temperatures but do not appear at this time to have the highly aligned structure necessary to produce high current-carrying capability.

Future work will concentrate on establishing optimum conditions for deposition and carrying out extensive physical characterization of the resulting films. To this end, a squid magnetometer has been installed and used to measure magnetic properties. Studies will attempt to correlate physical characteristics such as preferred orientation, critical current, critical temperature, and magnetization with microwave circuit performance.

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## R&D 100

### High-Speed Gallium Arsenide MESFET Optical Controller

One of the difficulties in implementing phased-array antenna structures for communications, radar, and sensing applications is the complexity of the feed and control interconnections. One possible approach to simplifying these interconnections is through the use of optical fibers for transmitting control signals, as well as radiofrequency signals, throughout the array. The use of optical fiber has the potential to reduce size, weight, and mechanical complexity; to allow transmission of higher data rates; and to reduce crosstalk and electromagnetic interference.

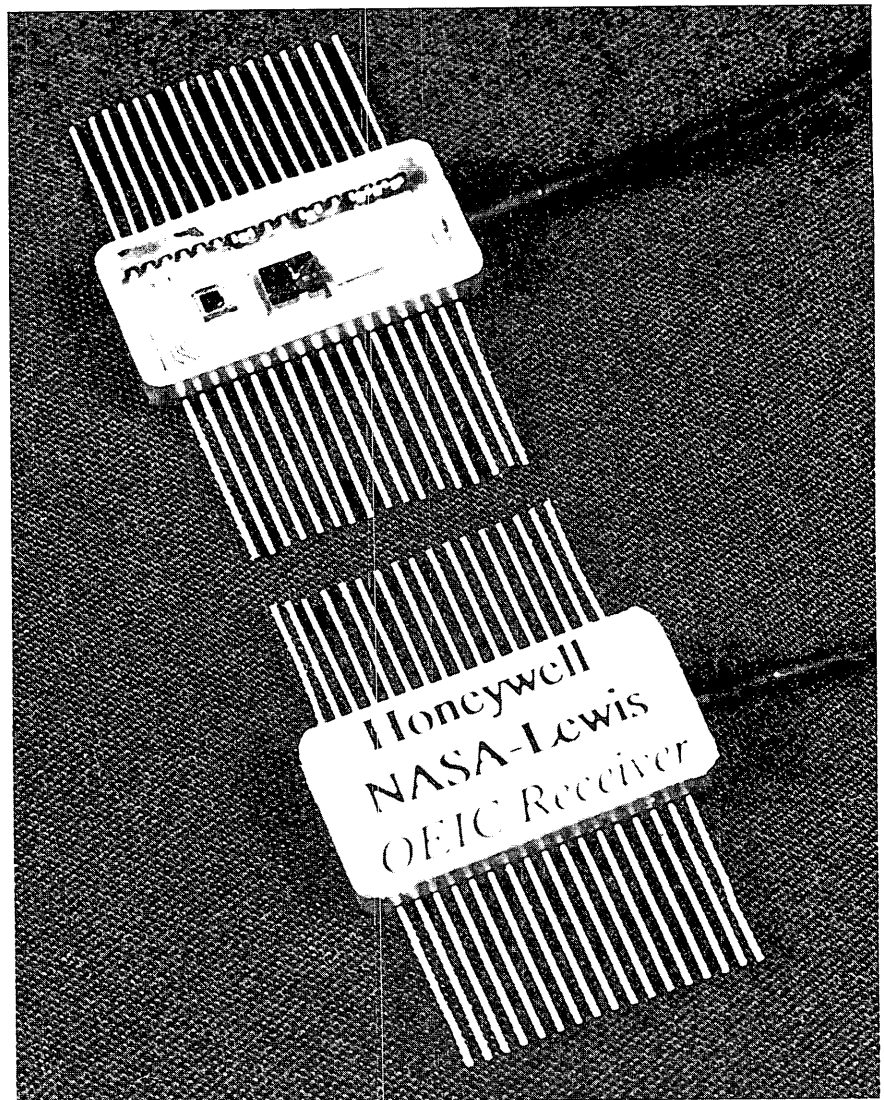
Over the last three years NASA Lewis developed a gallium arsenide chip capable of providing the interface between an optical fiber (carrying up to 1 Gbps of control data) and a monolithic microwave integrated circuit (MMIC). The chip utilizes technology so that it minimizes direct-current power requirements and may be integrated directly with MMIC circuitry if necessary.

In the last year a number of the chips have been delivered, and subsystem testing and evaluation have begun. Specifically, transmission and demultiplexing of high-speed data have been demonstrated as has control of an MMIC 32-GHz phase shifter. Demonstration of optical control of a small array is planned.

The interface chip was selected by Research & Development magazine as the winner of a 1989 R&D 100 award.

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*Optoelectronic integrated circuit in unsealed and sealed package 12.7 mm wide and 25.4 mm long*

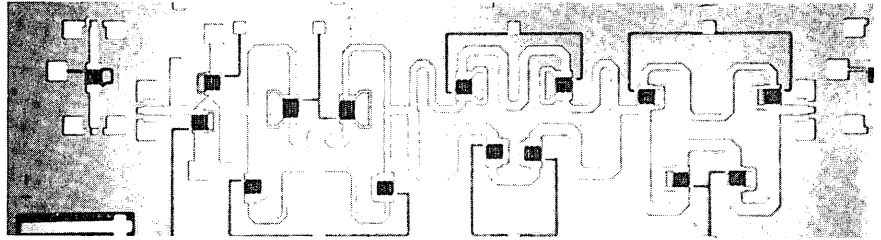


### 32-GHz Gallium Arsenide MMIC Phase Shifters

Monolithic phase shifters are a critical enabling component for any millimeter-wave system utilizing a phased-array antenna. In particular, Ka-band phased-array antennas are being considered for use on several deep-space communications links. Such a Ka-band phased-array system has several advantages over the presently used communications link, including rapid acquisition and tracking through electronic beam steering, minimized antenna package volume, reduced deployment complexities, and enhanced link margin and data rate capability.

Over the last year, as part of an on-going program, NASA Lewis has managed the development of a new phase shifter design at Minneapolis Honeywell. The new chip, in addition to being significantly smaller than previous versions, utilizes both switched- and loaded-line techniques to achieve the required four bits of phase shift. The module has exhibited 1.5 dB of insertion loss per bit, with an envelope of less than  $\pm 0.75$  dB variation with phase state. This characteristic is particularly important for operational systems, inasmuch as it minimizes the necessity for additional system gain variation to maintain output power as the phase state is varied.

Chips from this effort have been supplied to the Jet Propulsion Laboratory and used there together with MMIC power amplifier chips from other Lewis contracts in the development of breadboard demonstration arrays.



*Four-bit switched-line/loaded-line phase shifter*

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## Systems Integration, Test, and Evaluation Project

The Systems Integration, Test, and Evaluation (SITE) Project uses a unique, laboratory-based test facility to evaluate advanced satellite communications system technology. The test facility, designed and built at NASA Lewis, consists of a simulated satellite transponder integrated with high-data-rate digital ground terminals to present an accurate model of a satellite communications system. The test facility's flexibility allows evaluation of advanced system design concepts, component performance, hardware and software, and networking and control technology. System experiments such as performance, degradation due to interference, or signal attenuation effects due to rain are also performed. Major components of the facility such as high-power amplifiers and high-data-rate modems are the result of hardware development contracts. The digital ground terminals and transponder integration are entirely in-house efforts.

The first phase of the SITE project established a complete simulated satellite link. An extensive test program has evaluated the performance of numerous proof-of-concept components in a real digital data environment. The results of these tests have been reported at 7 conferences and in 20 publications. The second phase of the project, now under way, will expand the test facility into a multiple ground terminal network operating in a time-division multiple access format, including a radiative (30 and 20 GHz) link to a remote terminal.

In addition to the general communications research capabilities of SITE, the project also includes several

specific thrusts that support current and future NASA programs. In support of the ACTS program the SITE project provides experimental data that assist the ACTS flight and ground systems. Development of the high-burst-rate link evaluation ground terminal also relies heavily on SITE facilities and expertise. Another major SITE effort is the development of low-cost ground terminals for satellite communications applications.

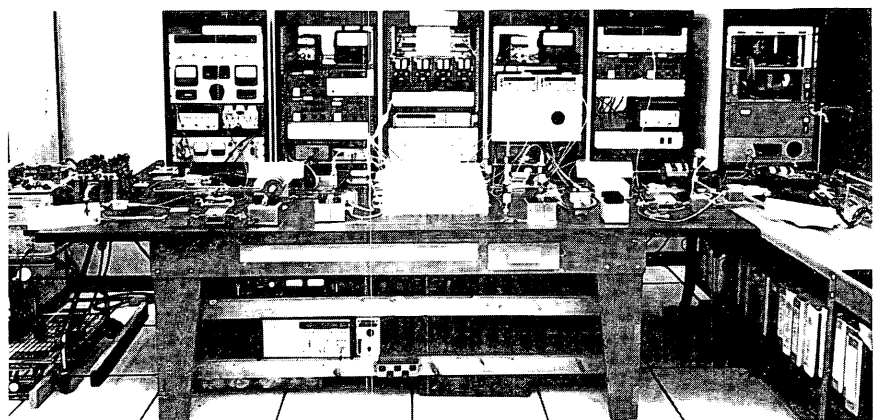
In the development of low-cost ground terminal systems and in support of SITE digital electronic systems, application-specific, integrated-circuit (ASIC) facilities have been implemented that will provide the state-of-the-art, computer-assisted-design features required in developing high-performance digital systems. The ASIC design capabilities are unique at Lewis and offer the increased performance and reliability in digital electronics necessary for the development of future space communications, power, and propulsion applications.

Ongoing expansion of the ASIC facilities will extend current capabilities into additional user support and increased design and analysis capabilities.

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*SITE test facility*

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### Low-Cost Portable ATS-3 Ground Terminal

A low-cost, highly efficient, user-friendly, portable ground terminal has been developed for use by emergency relief organizations on the Applications Technology Satellite (ATS-3) emergency-response satellite/terrestrial communications network. NASA, other Federal agencies, and private entities have sponsored or participated in experiments to demonstrate and evaluate satellite communications for search and rescue, disaster assessment and relief, and other incidents requiring emergency response. These experiments have primarily used highly mobile or portable ground terminals that operate with NASA's ATS-3. The Mexico City earthquake in 1985 exemplified the need for an easy-to-set-up-and-operate ground terminal: a great deal of time was lost as the medical doctors attempting to set up and operate ground terminals were frustrated by their lack of technical expertise. NASA Lewis was asked to develop a suitable portable terminal.

An amplitude-compandored, single-sideband (ACSB) modulation scheme was selected to provide a low-cost, narrow-bandwidth, low-power alternative to the currently used narrowband frequency-modulated system. Graceful degradation of the ACSB signal under weak signal conditions allows a lower gain and thus more compact antenna design for communications-quality transmissions and reduces transmitter power requirements to give extended operating time when the terminal is battery powered at a remote site. The packaged "transceiver" was designed to fit as carry-on luggage on commercial airplanes, and because of air safety restrictions, power is supplied from a car battery or its



*Low-cost portable ground terminal*

equivalent at the emergency site. In addition to voice modulation, provision for insertion of a data signal is included to allow research into a phase-shift-keyed alphanumeric (data) capability. The collapsible antenna was developed for NASA Lewis by M-Squared Enterprises; and Stephens Engineering Associates, a commercial manufacturer of ACSB land mobile radios, built the prototype portable ground terminal.

A number of radiofrequency tests have been performed on the prototype ATS-3 ACSB portable ground terminal, and the results are encouraging. A field test was made with the portable terminal located at a remote site, using the portable antenna for transmitting and receiving and a car battery for power. Performance of the unit was excellent, with consistently good reception of both the Malabar, Florida, ATS station and the NASA Lewis base station by the portable terminal. Acceptable reception of transmissions from the portable

terminal was reported by both base stations and estimated to be better than 12 dB (signal plus noise and distortion), even when the terminal was on "low" power (25 W peak envelope power (PEP); 50 W PEP is "high" power). Some degradation of performance was experienced as more simultaneous (FM) users were added to the satellite, but at no time was the signal lost completely.

The ACSB portable ground terminal is an inexpensive (less than \$3000) workable solution to the problem of providing emergency communications to remote locations throughout the Western Hemisphere. The American Red Cross is currently evaluating the terminal and plans to exercise the unit during a mock emergency to provide more accurate feedback on the practicality of the system during an emergency.

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## Advanced Modulation Technology

High-information-rate burst demodulators were identified by NASA Lewis as high-risk, high-cost components of satellite-switched, time-division multiple access (TDMA) communications systems. Efficient use of the frequency spectrum allocated for communications via satellite is also a major Government concern. Until recently, the U.S. communications industry relied heavily on foreign sources for high-performance TDMA modems. Advanced modulation and coding technology was required to significantly increase the bandwidth efficiency of TDMA modems for NASA and commercial applications while reducing their development risk and cost. Integrating the design of modulation and coding hardware was the approach pursued.

The Advanced Modulation Technology Development (AMTD) Project consisted of four contracts completed in fiscal 1989 to develop hardware models of bandwidth-efficient, high-rate TDMA demodulators. Ford Aerospace Corporation and TRW Electronic Systems Group have developed proof-of-concept demodulators for satellite applications, and COMSAT Laboratories and Harris Corporation have developed proof-of-concept models for ground terminal applications. These models have proven the theoretical concept of combining channel symbol encoding with modulation system design to obtain bandwidth efficiencies of at least 2 bps/Hz with an information rate of 200 Mbps, while maintaining system performance levels within 2 dB of theory.

In addition to the demanding spectral efficiency and information rate specifications, demonstration of the potential for low size, mass, and

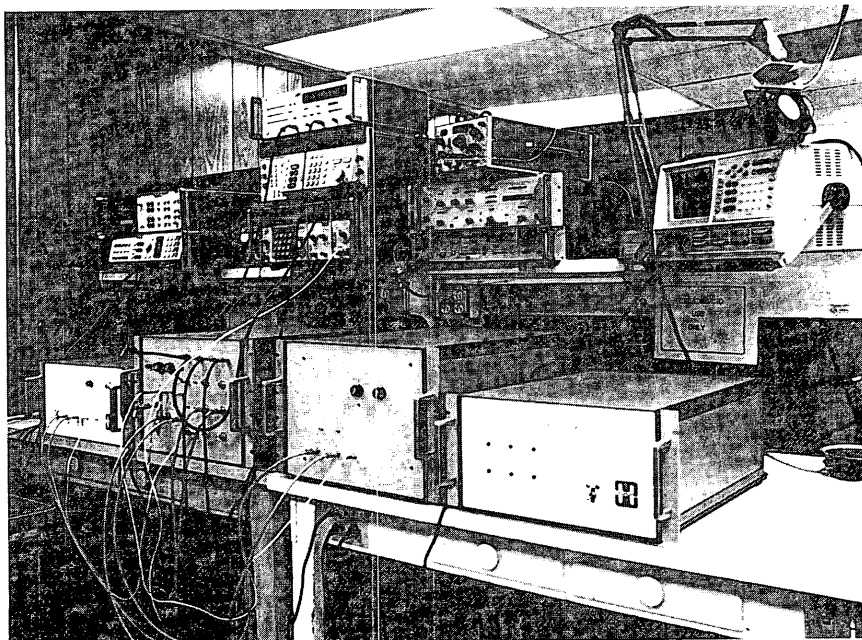
power consumption was required for the satellite demodulators and demonstration of the potential for efficient use of downlink power and low production cost was required for the ground terminal demodulators. All contractors developed compatible modulators, encoders, and other special test equipment to enable stand-alone testing and evaluation of the proof-of-concept hardware.

The completion of these contracts provided the basis for the Advanced Modulation and Coding Technology Conference held in Cleveland, Ohio, on June 21 and 22, 1989. All four contractors presented the results of their technology development contracts at the conference. COMSAT and Harris also demonstrated the working hardware.

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*Hardware model of bandwidth-efficient, high-rate TDMA demodulator*

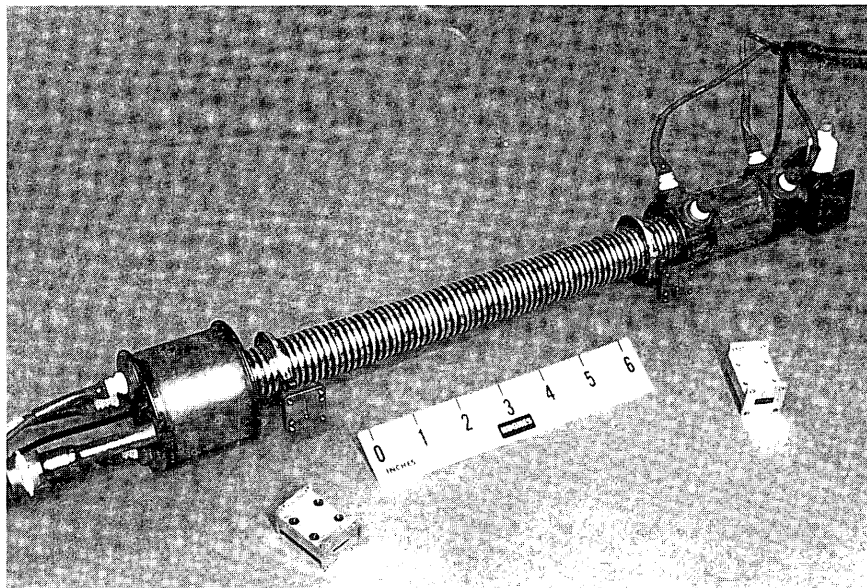
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### Highly Efficient K-Band Traveling-Wave Tube

In recent years NASA Lewis has developed a number of techniques that substantially improve the electrical efficiency of traveling-wave tubes (TWT's). These enhancement techniques, in conjunction with a novel fabrication process developed by Hughes Aircraft Company, are simultaneously being incorporated into a unique, highly efficient, 20-GHz TWT amplifier for application in future space communications systems.

Two TWT's are being fabricated as part of a multiyear research and development contract with Hughes. Each tube utilizes a helix type of slow-wave circuit with a dynamic multistage depressed collector (MDC), which recovers maximum kinetic energy from the spent electron beam. The collector electrodes were fabricated from ion-textured, isotropic graphite material with low secondary emission properties to reduce electron reflections and reemissions.

Key to the operation of the highly efficient tubes are tiny diamond segments that support the helix in the center of the slow-wave structure. The diamond segments remove heat from the helix by direct, high-pressure contact between the helix and an outer sleeve. The extremely high strength and outstanding thermal conductivity of the diamonds allow their cross section to be reduced to only 0.005 in. while maintaining a structurally sound assembly and an effective heat removal path. The small cross section, low dielectric constant, and extremely high thermal conductivity of the diamond perform synergistically to cool the helix without adversely distorting the electromagnetic fields of the radio-frequency signal.



*Highly efficient K-band traveling-wave tube*

The successful integration of diamonds required the development of a new fabrication technique. The new technique, using a compression fit with precise control of dimensional characteristics, holds the helix and diamond rod assembly together. This approach represents a significant improvement over earlier heat-shrink or force-fit approaches and is readily adaptable to higher frequency tubes that possess smaller internal structures.

Development of highly efficient TWT's was heavily dependent on computer analysis to optimize device performance. Computer codes previously developed at Lewis simulated and predicted electrical operation of the electron gun, the slow-wave structure, and collector sections of the tube. An extensive, new thermo-mechanical analysis was also conducted to study the structural integrity and the thermal-loading, and power-handling capabilities of the structure. Through the use of these codes the performance of each component was optimized and

matched prior to fabrication, thus obviating the need for time-consuming trial-and-error testing and greatly reducing the research cost.

The objectives of the research include an overall electrical efficiency of at least 60 percent with 75 W of continuous-wave radiofrequency output power at 20 GHz. The first TWT fabricated achieved an unprecedented 54 percent efficiency with 100 W of radiofrequency output power, representing nearly a 10-point efficiency improvement over similar devices currently being developed for space missions. A second TWT now being constructed has been further enhanced through additional computer simulation. This analysis indicates that the 60-percent efficiency goal is probably realizable. The transfer of these new capabilities and technologies to NASA missions and industry is under way, offering significant performance improvements and substantial cost benefits.

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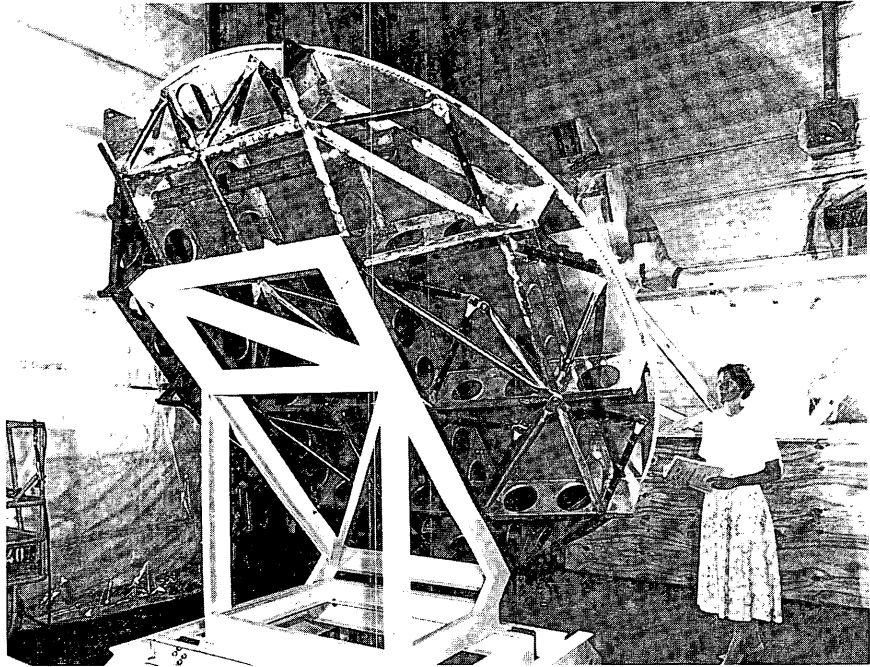
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## Precision Antenna Reflector Technology

The growth of communications satellite traffic has resulted in the use of ever higher frequencies as the lower communications frequency bands became crowded. This trend has led to the requirement for increasingly precise antenna reflectors. Typically, reflector accuracies of the radio-frequency wavelength divided by 100 have been required. At 30 GHz, this translates to a total reflector accuracy of 4 mils rms, including environmental effects. Achieving this accuracy on reflectors several meters in diameter represents a significant technical challenge.

Typical industry fabrication methods employ successive molding techniques for reflector facesheets and then a final fit-up to a master mold in order to achieve the required accuracies. Up to now, these methods have met the requirements. However, the cost of these reflectors has escalated and the limit of accuracy achievable with these methods appears to have been reached. Therefore, NASA Lewis is designing, analyzing, and fabricating precision antenna reflectors for antenna ground test systems and as proof-of-feasibility models for space antenna systems. A 1.4-m-diameter ground test antenna reflector has been built and radiofrequency tested, and a 2.7-m-diameter-antenna testbed reflector has been fabricated and coated with a reflective layer of vapor-deposited aluminum. The accuracy achieved on the 2.7-m-diameter reflector was 0.6 mil rms relative to a "best fit" parabola of revolution.

These antenna reflectors were constructed by first fabricating a relatively inexpensive, nonprecision,



*Back view of 2.7-m-diameter precision offset-fed antenna reflector for ground testing*

stainless steel backup structure. Stainless steel was selected for its long-term dimensional stability. Flat stainless steel honeycomb sandwich panels were then fastened to the backup structure, and machinable foam panels were adhesively bonded to the honeycomb panels. The foam was then machined to the rough contour. Two layers of fiberglass and a layer of epoxy surface compound were bonded to the rough machined surface. The surface compound was then machined to the final desired contour and a radiofrequency-reflective coating of aluminum was vapor deposited on the completed surface.

Solid reflectors for use on spacecraft can be fabricated in a similar manner from lightweight space-qualified materials. For example, the backup

structure and flat panels could be fabricated from honeycomb sandwich panels fabricated of graphite/epoxy, graphite/PEEK (polyetheretherketone), or similar stable materials. Machinable materials such as the low-density, sintered glass panels used as insulation on the space shuttle could be adhesively bonded to the flat panels. This surface could then be finish machined and reflective surface coated. Reflectors fabricated from these materials and with this method of construction would be accurate, lightweight, and dimensionally stable.

The main benefit of this method over conventional methods is the improved overall antenna performance through the improved accuracy gained by machining. Accuracy should also be improved because the angular

tolerances between the unidirectional layers of the composite facesheets of the flat honeycomb sandwich panels can be held better than on curved surfaces and thus will have more consistent planar isotropic properties. Also, since the final reflective surface is machined, contours other than figures of revolution can be fabricated if desired for particular missions. Costs for this method of fabrication should also be lower because accurate, expensive low- and high-temperature molds will not be required to achieve the desired accuracy. A patent application has been submitted for this work.

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### Microstrip Arrays Using Parasitic-Coupled Patch Antennas

In space communications applications involving antenna arrays, the printed microstrip antenna has significant advantages over conventional waveguide radiators because of its low cost and light weight. These patch antennas can be integrated with monolithic microwave integrated circuit (MMIC) devices to form active arrays with multiple functions. However, the inability of these antennas to achieve high gain and wide bandwidth places a constraint on the array performance. Over the past several years NASA Lewis has conducted research to enhance the gain and bandwidth of a microstrip antenna by using either coplanar or stacked parasitic patch antennas. It has been experimentally demonstrated that placing one or more parasitic patches over a

microstrip antenna results in a gain of over 10 dB and a bandwidth of more than 17 percent. This is a significant increase over the typical 4-dB gain and 3-percent bandwidth for a microstrip antenna without parasitic-coupled elements.

Using these high-gain parasitic elements in a microstrip array offers many advantages. An analytic study performed last year indicated that an array with parasitic elements generally has higher gain and lower sidelobe levels than an array without parasitic elements. Thus, the same array design requirements can be met with fewer active elements. Placing parasitic elements in microstrip arrays with MMIC phase and amplitude controls could result in fewer MMIC devices and simpler beam-forming network design.

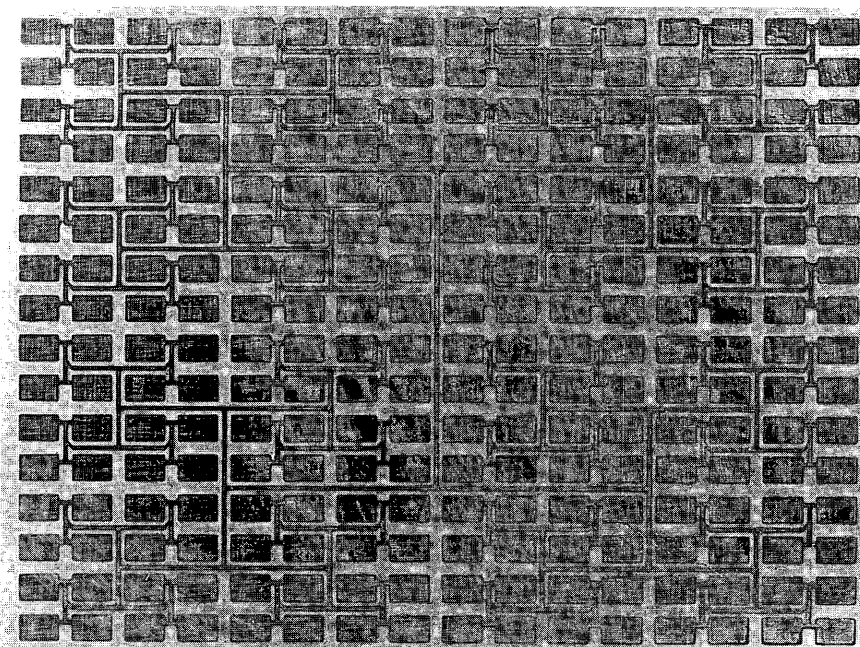
Recently, a  $16 \times 16$  microstrip array superimposed with a parasitic layer of identical design was tested at 18.4 GHz. Results of the measured patterns confirm that the array with parasitic elements has higher gain, lower sidelobe levels, and more than twice the impedance bandwidth of the array without parasitic elements.

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*16×16 microstrip array with microstrip feeding network*



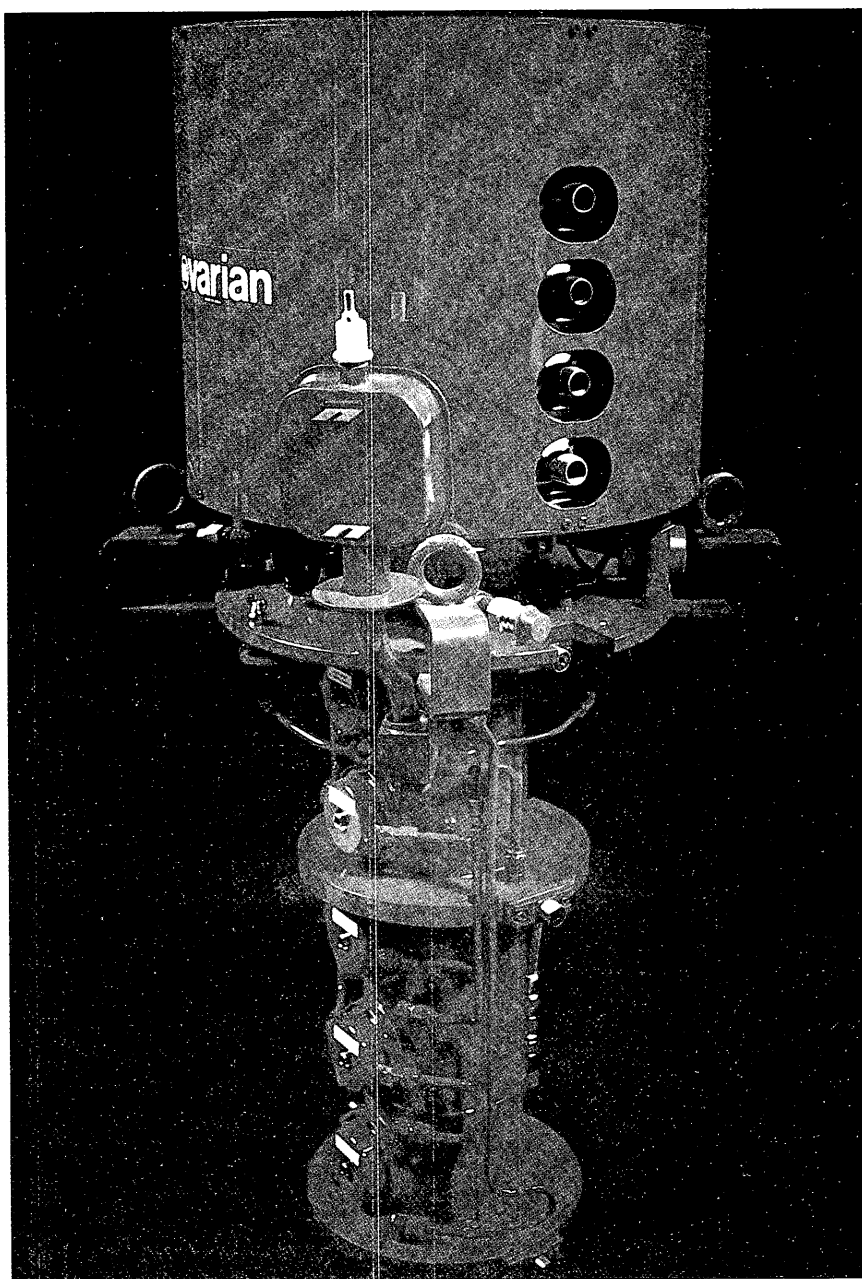
## R&D 100

### Klystron Amplifier for Multistage Depressed Collector

The multistage-depressed-collector (MSDC) klystron, which was recognized by Research & Development magazine as one of the 100 most significant technological advances in their 1989 R&D 100 competition, represents a textbook example of mating advanced space technology with industrial capability. It successfully combines the talents and resources of the NASA Lewis Research Center and the NASA Office of Technology Utilization, the development and manufacturing capability of Varian Associates, and the support of the television industry.

The energy-saving klystron is based on MSDC technology refined at NASA Lewis. Originally developed to enhance the efficiency of transmitters for communications satellites and other spacecraft, the MSDC works by recovering and using energy that is not needed for amplification. Previously, this energy was dissipated as waste heat.

Reducing energy consumption has been a long-time goal within the UHF television industry. A typical 60-kW UHF television station spends about \$60,000 annually for electricity alone. Klystrons amplify television signals to the power levels needed for transmission. Varian's multistage-depressed-collector klystron allows UHF stations to cut their transmitter power consumption in half—reducing operating costs and conserving energy resources. Consequently, a station could save \$30,000 a year, or 400,000 kWh of electricity. UHF transmitter manufacturers are already building new systems using the MSDC klystron, with the first one scheduled to go on the air in fall 1989.



*Klystron tube*

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## Power Generation

### Automotive Stirling Engine

An automotive Stirling engine has been developed under a U.S. Department of Energy (DOE) program to develop the technology for an alternative automotive powerplant. Lewis manages the Automotive Stirling Engine (ASE) Program for the DOE. The prime contractor is Mechanical Technology Inc. (MTI). The ASE program was completed in 1989 with a demonstration of program objectives and delivery of a Stirling-engine-powered postal van to the U.S. Postal Service for in-service evaluation on a mail route in the Northern Virginia-Washington, D.C. area.

The Mod II Stirling-engine-powered postal van (U.S. Postal Service long-life vehicle, LLV) underwent testing for emissions and economy at an EPA-certified chassis dynamometer facility. Fuel economy results were 19.6 mpg on the Federal driving cycle, 27.6 mpg on the highway cycle, and 22.5 mpg combined with unleaded gasoline. Emissions per mile were 0.41 g of hydrocarbons, 2.16 g of CO, and 0.82 g of NO<sub>x</sub>. The combined mileage of 22.5 mpg was 10 percent better than for the stock internal-combustion-engine-powered LLV in the same facility. Emissions easily met the current Federal standards without exhaust treatment. It is significant that neither a catalytic converter to clean the exhaust nor a muffler to silence the exhaust is needed for this engine. Although emissions did not meet the stricter Federal research standards for NO<sub>x</sub> of 0.4 g/mile, they could do so with increased exhaust gas recirculation.

The Mod II-powered LLV was also run head to head with a stock LLV over urban and highway road

courses in actual traffic to compare fuel economy directly. The Stirling-powered LLV gave 18.7 mpg on the urban course and 27.1 mpg on the highway course for a combined mileage of 21.7 mpg. The stock LLV gave 17.0 mpg and 24.9 mpg for a combined mileage of 19.8 mpg. These tests also indicated approximately a 10-percent improvement in overall mileage.

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# Facilities

## New Electromagnetic Interference Laboratory

An Electromagnetic Interference (EMI) Laboratory has been constructed to serve the Center's needs for qualifying flight hardware. This EMI laboratory is capable of providing standardized radiated and conducted emissions testing to support NASA Lewis' growing involvement in space-flight electronics development. The EMI laboratory, located in the Electric Propulsion Research Building, consists of a 12- by 16-ft radiofrequency-shielded enclosure and adjacent control room. The shielded enclosure was sized for systems as large as a double rack (for testing the Space Station *Freedom* combustion and fluids facility, for example) and has a 6-ft double door.

The equipment to be tested is located in the shielded enclosure to isolate it from the external electromagnetic environment. Electric and magnetic field sensors are fed through the enclosure wall to sensitive receivers in the control room. These receivers can measure interference over a frequency range of 16 Hz to 1 GHz. Computer-controlled testing and data acquisition provide standard-format spectral emissions data for out-of-tolerance comparison to requirements. Transient monitoring and transient generators are available as well to ensure compliance with military specifications or special space shuttle, Spacelab, or space station requirements. This initial operating capability is part of a three-year effort to construct a complete EMI facility including radiated susceptibility testing and to add a second shielded enclosure.

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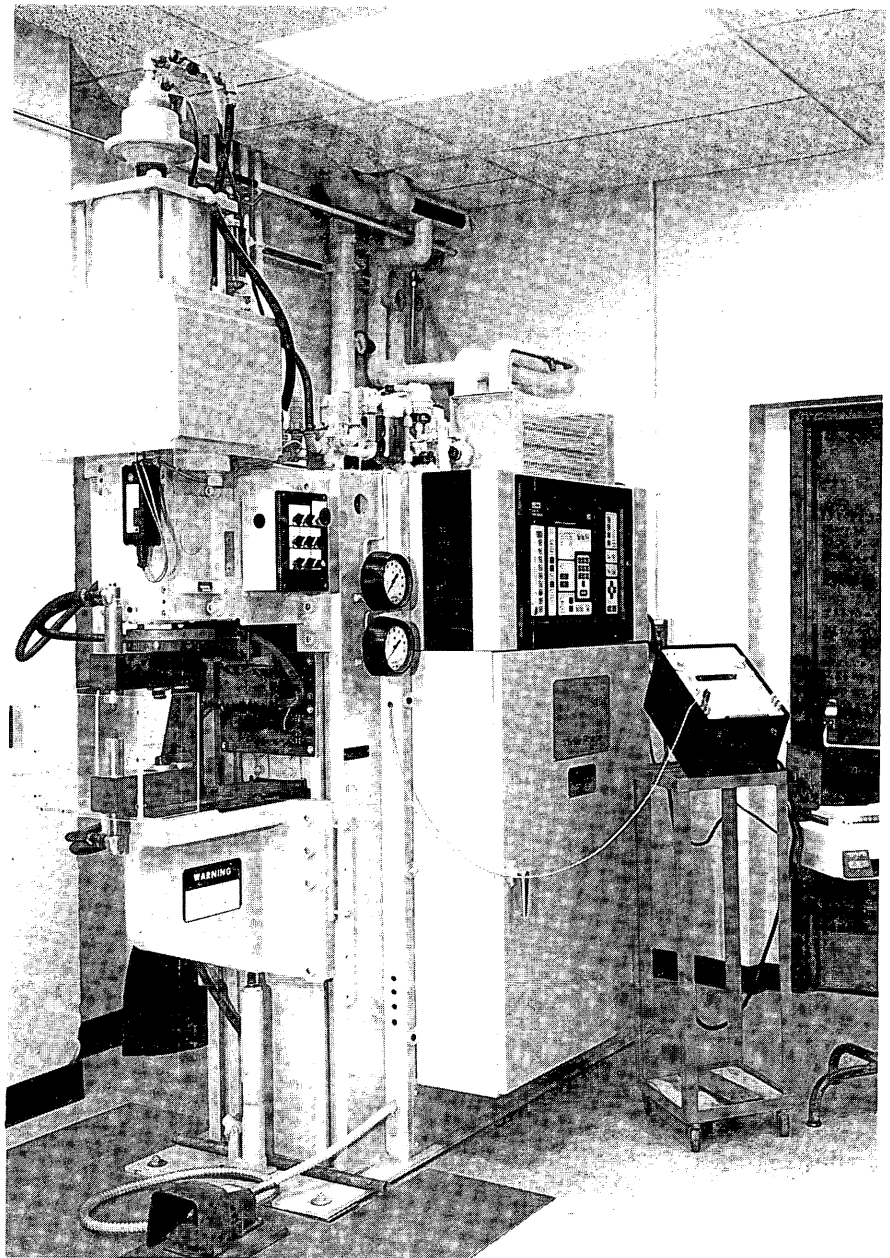
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ORIGINAL PAGE  
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NASA Lewis' Welding Research Laboratory supports materials research and development for advanced aerospace applications. Determining the weldability of all new materials is of major importance because sound joints suitable for the intended service are vital in all structural applications.

Four kinds of welding processes are available. One is resistance welding with a three-phase, 150-kVA, 90,000-A machine. This micro-processor-controlled machine can make spot, projection, and upset welds. The second process, brazing, can be programmed in vacuum or in argon to 1650 °C. The brazing furnace hot zone is 6 by 12 by 9 in. high. Solid-state welding, the third process, is accomplished in a hot press equipped with a programmable logic controller. The 6-in.-diameter by 6-in.-high hot press furnace operates to 1650 °C in vacuum, argon, or helium. Arc welding is the fourth process. For gas tungsten arc welding, a 300-A, alternating- or direct-current programmable power source is available. A glove port chamber can be used in an argon atmosphere. Atomic hydrogen arc welding can be accomplished with a 35-A, alternating-current power source and a tungsten electrode holder.

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*Resistance welding machine*

## Test Buildup Area Modifications at Cryogenic Components Laboratory

The Cryogenic Components Laboratory was originally constructed in 1961. Its primary function is basic research on the behavior of materials at cryogenic temperatures, especially in liquid hydrogen. The facility consists of six remote test cells separated by bunkers and operated from a central control building. The control building also houses technicians that operate the facility and has a service shop, an instrument shop, a control room, and an office shop.

Research at the Cryogenic Components Laboratory (CCL) involves cryogenic testing of rocket engine turbomachinery components, such as pumps, bearings, and seals. Other experiments at this facility involve the cryogenic testing of various aerospace materials that support the space station, the orbital transfer vehicle, the liquid-oxygen hydrocarbon booster, and the transatmospheric vehicle. In addition to supporting the six test cells the service shop supports tests conducted at the neighboring Rocket Engine Test Facility (RETF). For more than a year RETF test packages have been prepared in the CCL service shop. For safety reasons, buildup work on any of the three busy RETF test stands cannot proceed while testing occurs at another. Preparing the experimental packages at a remote location such as the CCL allows the RETF to be a more productive facility.

Rehabilitation and modification of the Cryogenic Components Laboratory was required so that the facility could continue to support the work in the CCL test cells and the experimental buildups for RETF. A new area for experimental package

buildup and critical parts assembly was required to support the RETF programs. In addition, the CCL control room expansion now better utilizes the existing test cells at CCL. The new shop office and the relocated computer and sensor room resulted in improved productivity and facility utilization in both of these busy research facilities.

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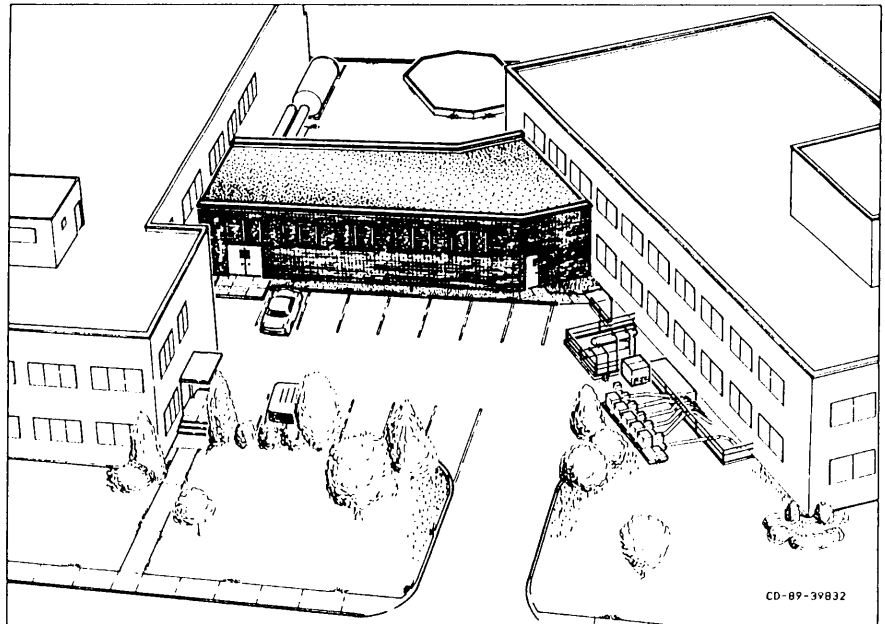
*Cryogenic Components Laboratory*

## New Annex for Materials and Structures Laboratory

The Materials and Structures Laboratory is used to conduct a wide variety of research. Materials research deals with superalloys, powder metals, ceramics, polymers, and composites under extreme environmental conditions. Structures research includes computational structural mechanics, structural dynamics, fatigue and fracture, life prediction, and nondestructive evaluation. Special capabilities include a laboratory for evaluating materials under cryogenic and high tensile, creep rupture, and fatigue and fracture conditions; high-velocity burner rigs for simulating engine cycles; a variety of furnaces for melting and heating; a laboratory for materials processing; a laboratory for metallurgical and chemical analysis; a laboratory for conducting tribology studies; facilities for investigating forced and resonance-induced vibrations in rotating machinery; and a laboratory for nondestructively evaluating materials and structures.

A new addition to the Materials and Structures Laboratory, constructed as an annex, provides 2970 ft<sup>2</sup> of floor space. The annex, called the Fatigue and Fracture Laboratory, consists of a laboratory area to house cyclic test machines with ancillary equipment, a calibration room, and a control room. This addition permits testing of advanced materials for the hypersonic and HITEMP programs.

The annex is a one-story masonry building with a concrete floor and steel roof framing. The floor has a continuous trench around the complete perimeter to carry the hydraulics and cooling water for the test systems. Construction work also included heating, ventilating, and air



*Architectural rendering of Materials and Structures Laboratory annex*

conditioning and water, sewer, electrical, and safety systems. The annex was built adjacent to the existing Materials and Structures Laboratory for efficient use of existing central support services such as 3000-psi hydraulics, cooling water, and dedicated computer facilities.

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# Aeropropulsion

## Strategic Objectives

- To strengthen our position as the principal NASA center for the advancement of aeropropulsion technology that will significantly contribute to the continuing preeminence of U.S. civil and military aircraft.
- To become the Nation's pathfinder in innovative aerospace propulsion research and technology.

# Programs

## Propulsion System for National Aerospace Plane

NASA Lewis is conducting research and development related to the propulsion system for the national aerospace plane (NASP) X-30 vehicle. This work includes inlets, nozzles, combustion, controls, hydrogen propellants, materials, and structures. Lewis has conducted tests of inlet concepts and hydrogen-fueled engine systems to demonstrate advanced propulsion concepts. Balancing the high-speed and low-speed operating characteristics of the components and the propulsion system has been a major focus of these efforts. Wind tunnel testing of an inlet for a Mach 5 engine system was completed this year. This test demonstrated inlet performance with boundary layer bleed and obtained data for verifying analytical flow codes. Fundamental experiments were also conducted this year to assess transonic and supersonic nozzle performance and the feasibility of using external burning for transonic drag reduction.

Analytical codes are being developed to predict the high-speed internal flows in the engine components and to predict the characteristics of metal-matrix composite structures. Work is proceeding under Lewis' direction to develop slush hydrogen, a mixture of approximately 50-percent solid hydrogen suspended within liquid hydrogen, as a usable fuel. Other propellant work is focused on converting parahydrogen to the ortho state by using advanced catalysts in order to provide a 20-percent increase in heat sink capacity for structural cooling.

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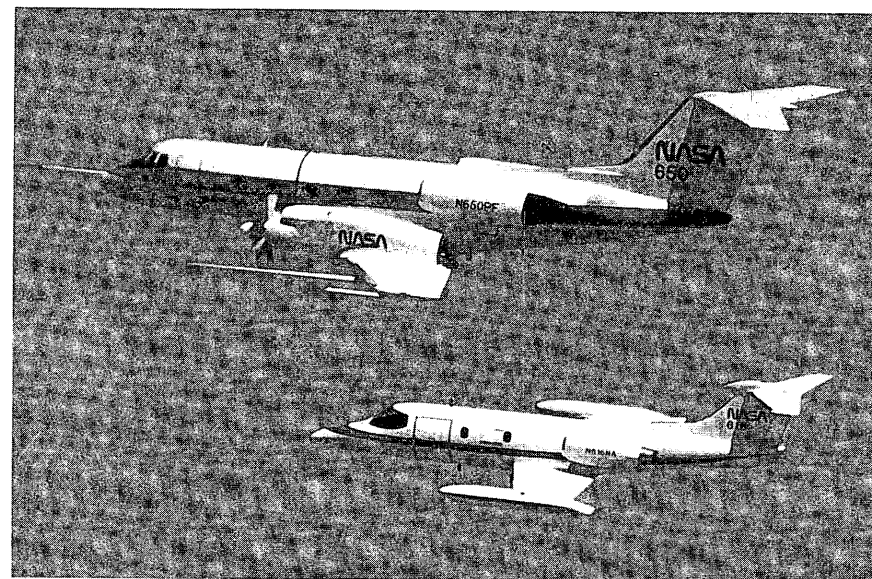
*Artist's concept of national aerospace plane*



## In-Flight Measurements of Advanced Turboprop Aerodynamics and Acoustics

After an extensive aeroelastic and acoustic flight test program by Lockheed, the Propfan Test Assessment (PTA) aircraft became available to NASA Lewis for additional flight testing. Four aerodynamic and acoustic flight experiments were conducted: an en route noise test, a structure-borne noise test, an unsteady-propfan-blade-pressure measurement test, and a video thermography test.

**En route noise test.**—The PTA aircraft was flown repeatedly directly over a linear ground microphone array established by NASA Langley Research Center with Federal Aviation Administration assistance at the White Sands Missile Range. Flights were conducted at altitudes of 1000 to 30,000 ft above ground level at flight speeds up to Mach 0.77. Weather balloons were released regularly to measure atmospheric temperature, humidity, and wind velocity and direction versus altitude. Atmospheric attenuation for the propeller tones was calculated from the measured atmospheric properties. PTA source noise levels and directivities were measured by flying the instrumented Lewis Learjet in formation at selected positions relative to the PTA aircraft. Conventional and video cameras were used to position the Learjet and to record and measure distances and angles. With a known aircraft noise source, known weather conditions, and a given atmospheric attenuation model, calculated ground noise levels can be checked against the observed values.



*Propfan Test Assessment aircraft with microphone-equipped Learjet*

**Structure-borne noise test.**—The objective of this ground test was to further the development of a methodology for calculating structure-borne noise inside the cabin of an airplane in flight. Structure-borne noise normally cannot be measured directly because of the dominance of airborne noise. Southwest Research Institute investigators excited the PTA left wing with two oppositely phased shakers. Transfer functions were obtained that related wing motion as measured by strain gages and acoustic signals inside the cabin. Cabin interior structure-borne noise will be calculated by applying the transfer functions to previously measured strain gage readings at selected flight conditions.

**Blade pressure measurement.**—The unsteady pressures at 30 selected locations on the pressure and suction surfaces of a specially instrumented propfan blade were measured. Hamilton Standard, under NASA contract, designed, fabricated, and installed the unsteady-blade-pressure measurement system. Steady and unsteady (dynamic) pressure measurements obtained for several altitude and propeller operating conditions at three nacelle tilt angles will be used to validate propeller design codes and to provide a data base for aerodynamic and noise prediction analyses. An improved understanding of tip vortex flow, leading-edge vortex flow, shock waves, and other flow phenomena will result.

**Video thermography test.**—The temperature distributions on both sides of the SR-7L blade were measured in flight at several altitudes up to 25,000 ft and at a number of selected engine operating conditions. A special argon-cooled infrared video camera was used to record blade temperature. In order to provide a clear unimpeded optical path between the cabin-mounted camera and the propfan, an opening was made in the cabin window, and the test was conducted with an unpressurized cabin. Blade surface temperatures will be used to improve the accuracy of the unsteady pressure transducer data. Research on propeller icing will also benefit from this information.

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### **Advanced Short-Takeoff/Vertical Landing Fighter Concept**

Advanced supersonic fighter aircraft with short takeoff and vertical landing (STOVL) capability offer attractive operational advantages to the military services. In the past these aircraft have been prone to penalties in weight, payload, and range owing to the necessary addition of aircraft and propulsion system features to enable STOVL flight. Advanced propulsion technology is recognized as the key to great reductions in these penalties. At least four single-engine propulsion approaches are capable of achieving an advanced STOVL supersonic fighter—all needing a variety of technology developments.

As part of the Joint U.S./U.K. Advanced STOVL Technology Program a study was devised to define the specific technology developments required and to identify the key features and advantages of the competing concepts. NASA Lewis performed the propulsion aspects of these studies with General Electric, Pratt & Whitney, and Allison as prime contractors. NASA Ames Research Center performed the aircraft aspects with General Dynamics, McDonnell Douglas, Lockheed, and Grumman as prime contractors. Each airframe contractor studied only one preferred propulsion concept by teaming with a propulsion contractor for the engine/airframe integration activity.

In order to improve comparability of the results from different U.S. contractors, a NASA, Air Force, and Navy team "normalized" their designs. The mission requirements were still achieved but with adjusted weights and performance. Officials of the United Kingdom, who had

sponsored a similar set of studies with their engine and airframe manufacturers, then met jointly with the U.S. team to assess and rank the aircraft and propulsion concepts.

The conclusions of the studies and the U.S./U.K. joint assessment are having a major impact on the direction of STOVL research activities. Concepts with remote lift jet systems were found to provide better options for engine location within the airframe, allowing greater freedom of configuration. Conventional mixed-flow propulsion during wingborne flight (i.e., all of the engine gas exhausting through a single propulsion nozzle) provides better augmented performance and superior nozzle/airframe integration.

An ASTOVL Technology Program plan has been developed on the basis of these conclusions. This plan addresses the development of the high-risk, critical technologies that would allow the military to make informed decisions about future STOVL supersonic fighter requirements. NASA Lewis has already begun to pursue STOVL propulsion technology development in response to this plan. The recently calibrated Powered-Lift Facility is being used to evaluate vertical-lift exhaust nozzle concepts and will soon be used for diverter valve and off-take ducts as well as further ejector augmentor evaluations. Corresponding analytical tools such as PARC-3D are being calibrated and will be available to assist designers of STOVL-powered lift components. The main elements of the approximately five-year plan are diverter valves and transport ducts, aircraft and ground environment, hot gas ingestion, air-

craft controls and handling qualities, propulsion controls, vertical-lift nozzles and blockers, and propulsive lift augmenters.

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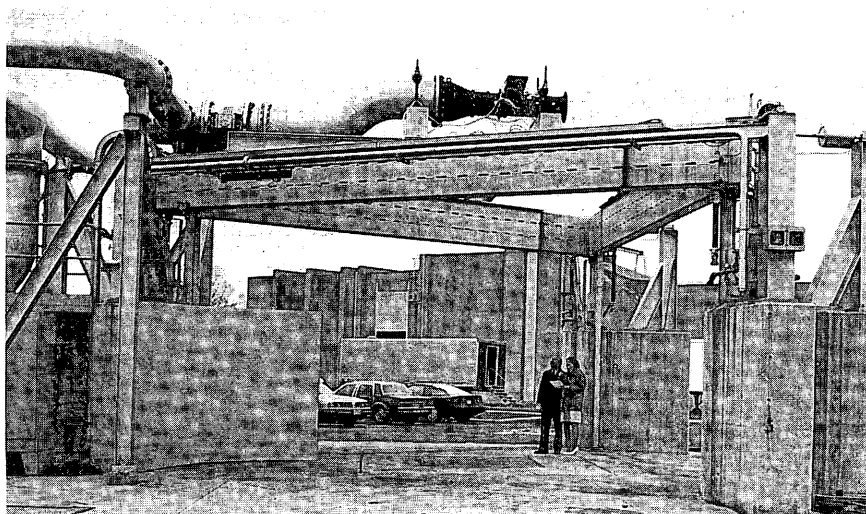
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### Advanced High-Temperature Engine Materials Technology

The objective of the Advanced High-Temperature Engine Materials Technology (HITEMP) Program is to generate technology for revolutionary advances in composite materials and their structural analysis to enable the development of 21st century civil propulsion systems with greatly increased fuel economy, improved reliability, extended life, and reduced operating costs. The primary focus is on polymeric, metallic, intermetallic, and ceramic matrix composites. These composite materials are being developed for eventual use in fans, compressors, turbines, combustors, and exhaust nozzles of future civil transport aircraft.

NASA Lewis aeronautics and aerospace technology researchers and their counterparts in industry and universities are defining composite property requirements for advanced engine applications.

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*Powered-Lift Facility*

Lewis materials researchers have developed new chemical formulations and processing techniques to raise the use temperature of polymeric matrix composites. Potential fibers for intermetallic matrix composites have been identified through a thermodynamic screening approach, and single-crystal fibers have been grown in a laser floating-zone facility here at Lewis. The technology to process a Lewis-developed ceramic matrix composite has been transferred to the aircraft engine industry.

Lewis structures researchers have developed models for predicting the stress-strain behavior of composites, and industry is using these models for their research. Other models are being used to guide the selection of

the constituents of intermetallic composites. New test methods permit mechanical property testing of intermetallic matrix composites to 1100 °C (2000 °F), and non-destructive evaluation techniques are improving composite materials processing.

An annual review of the HITEMP program was held from October 31 to November 2, 1989. Details of research accomplishments are published in a conference report.

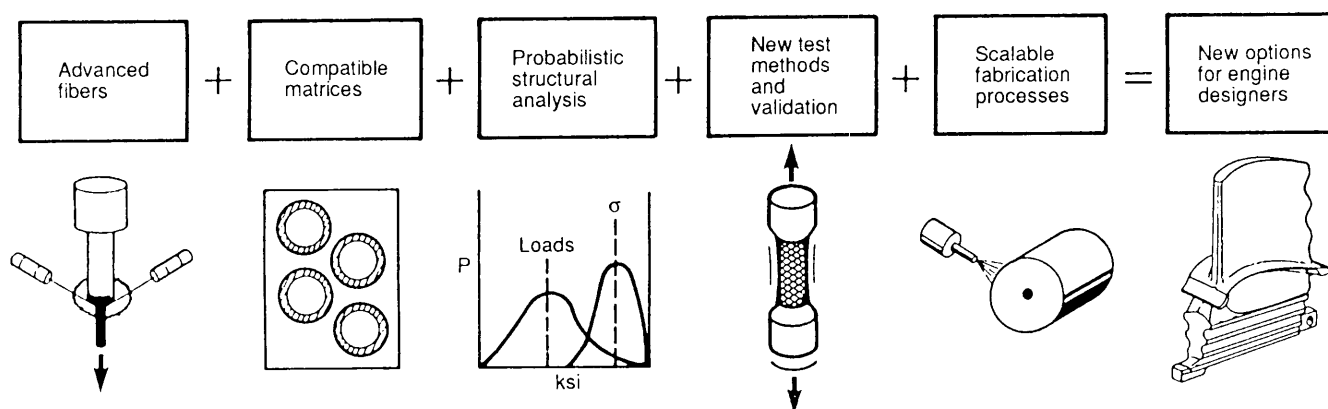
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*Elements of HITEMP program*

# Research & Technology

## Materials

### Oxidation Limits for NiAl + Zr

The nickel aluminide  $\beta$ -NiAl is a primary contender as the matrix material in fiber-reinforced composites for advanced turbine applications. This is due, in part, to its superior oxidation resistance conferred by the formation of protective  $\alpha$ -Al<sub>2</sub>O<sub>3</sub> scales. In previous studies at NASA Lewis, cyclic oxidation tests revealed the optimum composition to be Ni-50Al-0.1Zr (in atomic percent), where doping with reactive elements (Zr) is necessary to maximize scale adhesion. However, results from cyclic oxidation tests in themselves do not provide a physical measure of metal degradation. Recent studies used a cyclic oxidation spalling program (COSP) developed at NASA Lewis to arrive at specific metal consumption values due to cyclic oxidation of bulk NiAl + Zr alloys. A limiting criterion was developed, based on a change in oxidation mechanisms, for determining either lifetime at a given use temperature or a maximum use temperature for a given lifetime.

A specific aluminum consumption of 5 mg/cm<sup>2</sup> was chosen to be a conservative lifetime criterion because this was the approximate point at which less-protective NiAl<sub>2</sub>O<sub>4</sub> was observed in the scale. On the basis of this criterion the following cyclic oxidation lifetimes and maximum use temperatures were determined:

Temperature, °C	Lifetime, hr
1100	46,900
1200	2,810
1300	266
1400	39
1500	9

Lifetime, hr	Maximum use temperature, °C
10	1493
100	1348
1000	1241
10,000	1153

These maximum use temperatures and lifetimes were calculated from an equation obtained by plotting the criterion as a function of time and temperature. The equation is

$$\log(t) = b_1 + b_2T + b_3T^2$$

where

$t$  time, hr

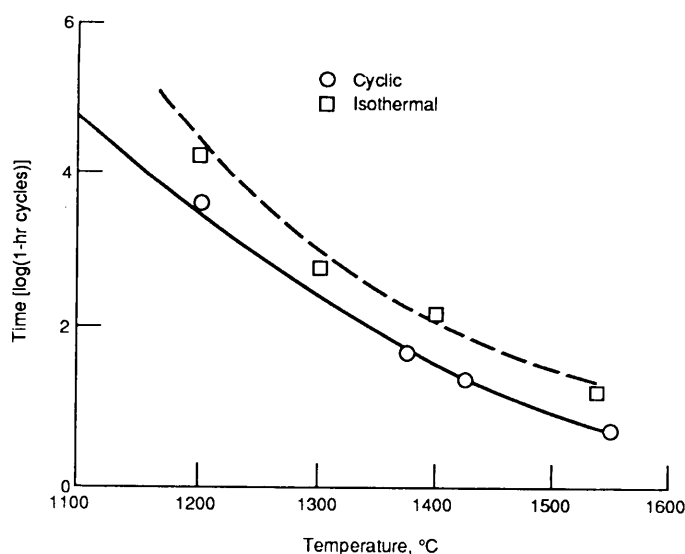
$T$  temperature, °C

$b_1$  31.07

$b_2$  -0.0348

$b_3$  0.00000982

The error in  $\log(t)$  is  $\pm 0.113$ .



Limiting criterion as a function of cyclic oxidation lifetime and maximum use temperature for isothermal and cyclic oxidation of stoichiometric NiAl + Zr

Based on the same criterion, corresponding isothermal oxidation lifetimes are longer and maximum use temperatures are higher. The improvement in isothermal oxidation arises from the lack of scale spallation and from the resultant faster oxide growth. The limiting times and temperatures for isothermal oxidation based on the 5-mg/cm<sup>2</sup> aluminum consumption criterion represent an optimum upper limit for NiAl + Zr.

Ongoing studies involve alloy diffusion modeling to validate the present work and to predict lifetimes for NiAl coatings.

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#### Oxidative Stability of SiC/Si<sub>3</sub>N<sub>4</sub> Composites

A high-temperature, fiber-reinforced ceramic composite has been developed at NASA Lewis under the HITEMP program. The composite consists of a porous silicon nitride (Si<sub>3</sub>N<sub>4</sub>) matrix reinforced by continuous silicon carbide (SiC) fibers. In the as-fabricated condition the SiC/Si<sub>3</sub>N<sub>4</sub> composites display a metal-like stress-strain behavior, graceful failure beyond matrix fracture, and strength properties superior to those of comparably dense unreinforced Si<sub>3</sub>N<sub>4</sub>. However, a major issue is whether these excellent properties can be retained after long-term exposure to thermal and environmental conditions similar to those of high-performance engines.

Composites subjected to a 100-hr exposure test in an oxidizing environment in the temperature range 1200 to 1400 °C show excellent strength retention. In contrast, composites exposed at 600 to 1000 °C show strength loss. It has been determined from electron microscopy and interfacial bonding studies that the primary mechanism responsible for strength loss is oxidation of the carbon-rich fiber surface coating, which causes loss of bonding between the fiber and the matrix as well as fiber degradation. At temperatures beyond 1200 °C, however, growth of a glassy oxide layer on the external surfaces of the composite reduces the inward diffusion of oxygen and therefore slows oxidation of the fiber coating. This promotes greater strength retention. It is anticipated that the long-term oxidative stability of the composite at intermediate temperatures can be

improved by providing an oxidation-resistant surface coating on the SiC fibers, by sealing off the porous matrix surface, or by fully densifying the matrix.

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## Effects of High-Pressure Nitrogen on Thermal Stability of SiC Fibers

Strong, thermally stable, small-diameter ceramic fibers are crucial to the development of tough ceramic matrix composites. Small-diameter SiC fibers that have adequate strength are commercially available. However, these fibers are not microstructurally stable beyond 1200 °C. The lack of thermal stability lowers not only the composite use temperature but also the fabrication temperature, which is generally higher than the intended use temperature. Therefore, the fibers may be degraded before the composites are put into use. The objective of this work was to improve the thermal stability of Nicalon SiC fibers through heat treatment in high-pressure gases in order to maintain fiber properties during composite processing.

Nicalon fibers are derived from polycarbosilane polymer precursors. Because the fibers are cured in air, they do not completely convert to SiC but are instead a mixture of SiC, SiO<sub>2</sub>, and excess carbon. At elevated temperatures reactions between SiO<sub>2</sub> and carbon are believed to increase porosity and flaw growth and therefore weaken the fibers. In this work fibers were treated for 1 hr in 50- and 7-atm nitrogen at temperatures ranging from 1000 to 1800 °C. Single fibers were tensile tested at room temperature after thermal and pressure treatments. It was found that high-pressure nitrogen was effective in delaying the reactions responsible for strength loss.

High pressure alone can limit the strength loss to a certain degree, as was found with earlier studies of high pressures of inert gas. The nitrogen, however, was able to react

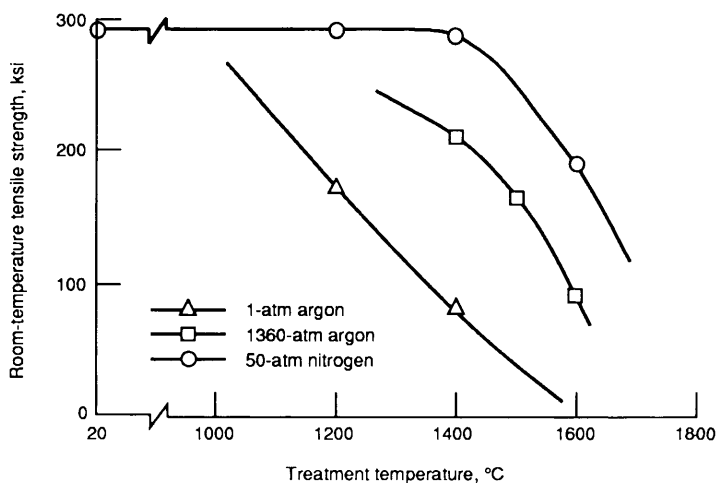
slightly with the fiber to produce fibers with more stable chemical compositions, grain structures, and mechanical properties.

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*Processing in high-pressure nitrogen raises temperature limit for retention of Nicalon SiC fiber strength (test time, 1 hr)*

## Ceramic Matrix Composites From Polymer Precursors

The application of ceramic matrix composites in high-temperature engines requires the development of processing techniques that permit small-diameter fibers to be incorporated and allow complex shapes to be formed. Processing temperatures need to be kept low enough to avert fiber damage and chemical reaction between the matrix and the fiber. The use of polymers as precursors to ceramic matrices provides both low-temperature processing and complex-shape-forming capabilities using technology developed for resin matrix composites.

Studies have been under way at NASA Lewis to develop ceramic composite matrices by the controlled pyrolysis of polysilsesquioxanes. The polymer precursors are readily formed by hydrolysis and condensation of trifunctional ethoxysilanes. A series of phenyl- and methyl-silsesquioxane homopolymers and copolymers have been characterized. Pyrolysis in flowing argon produces char yields of nominally 70 to 75 percent. The resulting ceramic has been characterized as a silicon oxycarbide at temperatures to 1500 °C. At 1500 °C and low argon flow rates or in an enclosed Al<sub>2</sub>O<sub>3</sub> crucible, the ceramic undergoes carbothermal reduction to form β-SiC. Increasing the ratio of phenyl to methyl groups in the copolymer has been shown by microprobe analysis to increase the carbon content of the oxycarbide product.

Composites of Nicalon fiber in polysilsesquioxane-derived ceramic matrices have been fabricated by filament winding and hot pressing below 200 °C, followed by pyrolysis in argon to 1200 °C. Pyrolysis

under ambient pressure conditions results in a matrix that is highly microcracked normal to the fiber direction. The degree of microcracking is somewhat diminished for the higher-carbon-content matrices. Significant increase in mechanical properties has been achieved by pyrolysis under high pressure. Whereas composites pyrolyzed at 1 atm to 525 °C failed on machining, those pyrolyzed at 15 ksi to 650 °C exhibited four-point flexural strengths of 34 ksi and composite failure. Further heat treatment to 1200 °C produced materials with flexural strengths of 20 to 24 ksi, regardless of initial pyrolysis pressure. This decrease in strength may be the result of reactions at the fiber-matrix interface, possibly from the presence of small concentrations of oxygen in the purge gas. Pressure pyrolysis studies are continuing as part of a joint program with Fiber Materials, Inc. Heat treatment in purified argon is being investigated as a means of averting interfacial reactions.

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### Single-Crystal Fiber Development

Advanced aircraft currently being developed will require advanced lightweight materials with good high-temperature properties. Fiber-reinforced metallic and intermetallic matrix composites have the potential for meeting these requirements. However, many existing reinforcing fibers are not chemically compatible with the proposed matrix materials. In addition, the considerable thermal expansion mismatch between the fiber and matrix materials can cause problems during thermal cycling.

As part of an ongoing effort at NASA Lewis on high-strength, high-temperature fiber development, a laser-heated, floating-zone apparatus was designed and built. This apparatus is being used to grow research quantities of single-crystal fibers that may meet the chemical, physical, and mechanical requirements for use in high-temperature composites. In this system two laser beams are focused onto a small-diameter feed rod of the desired material. The laser beams melt the tip of the feed rod, creating a liquid drop that is supported on top of the feed rod. A single-crystal seed of the same material is lowered into the liquid drop, causing a portion of the single-crystal seed to melt. The seed crystal is withdrawn from the melt at the same time that the feed rod is raised into the laser beams, causing a single-crystal fiber to be withdrawn from the stable pool of liquid material. The speed and relative motion of the top and lower pull heads determine the diameter of the solidified single-crystal fiber. The control of the laser power determines the temperature of the molten zone. With the temperature of the molten zone held constant and the speed of the top and lower pull

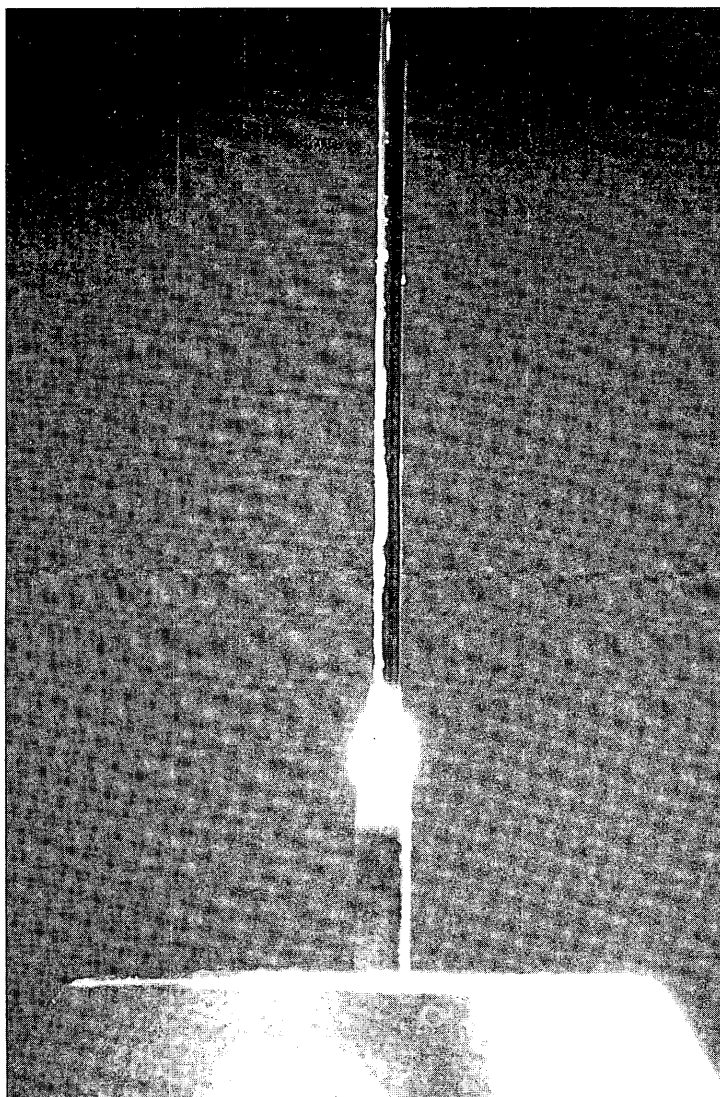
heads fixed, a uniform single-crystal fiber can be produced from almost any material that has a stable liquid.

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#### Bibliography

Westfall, L.J.; McDanel, D.L.; and Petrasek, D.W.: Advanced Fiber Development for Intermetallic Matrix Composites. NASA TM-102109, 1989.

ORIGINAL PAGE  
BLACK AND WHITE PHOTOGRAPH



*Ruby fiber ( $\text{Al}_2\text{O}_3$ -1.5% $\text{Cr}_2\text{O}_3$ ) produced by floating-zone apparatus*

## Nitrogen Postcure Treatment of Polymer Matrix Composites

Polymer matrix composites such as graphite-reinforced PMR-15 and PMR-II are finding wider acceptance as aeropropulsion materials. Because composites offer both ease of fabrication and high specific strength, they can reduce aircraft weight and manufacturing costs. However, the relatively low thermal-oxidative stability of these systems limits their use to those regions of the engine operating at temperatures between 550 and 600 °F (288 and 316 °C). New polymer matrix composites with improved thermal-oxidative stability or methods of improving existing composites would increase their use in advanced aircraft and lead to higher thrust-to-weight-ratio engines.

A research program is in progress at NASA Lewis to develop new polymer matrix composites for extended use in air at 800 °F (425 °C). Use of polymer matrix composites at these temperatures requires low weight loss and good retention of mechanical properties during high-temperature exposure, as well as good initial high-temperature mechanical properties. The high-temperature mechanical properties of a polymer or a polymer matrix composite are dictated by the glass transition temperature  $T_g$  of the polymer. At  $T_g$  the polymer undergoes a transformation from a glassy to a rubbery state. For a polymer matrix composite to have good mechanical properties at 800 °F (425 °C), the polymer matrix must have a  $T_g$  of at least 850 °F (450 °C).

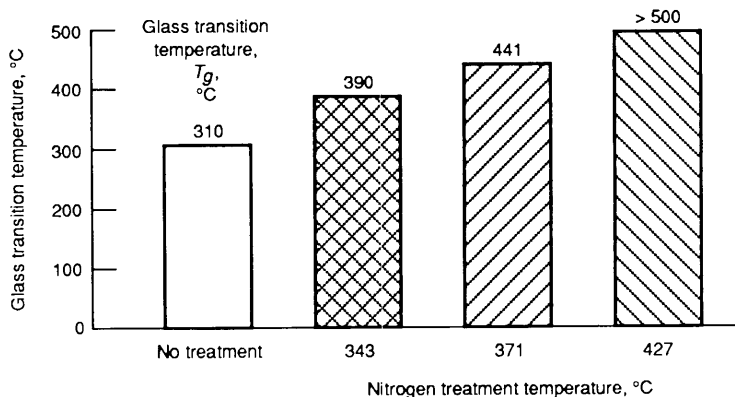
Recent studies on the postcuring of graphite-reinforced PMR-15 laminates revealed that treating these laminates in nitrogen at elevated

temperatures significantly increased the glass transition temperature and the 700 °F (371 °C) flexural strength of these composites.

Nitrogen postcuring at 800 °F (425 °C) for 24 hr raised the glass transition temperature above 932 °F (500 °C). Nitrogen postcuring at 700 °F (371 °C) doubled the high-temperature flexural strength over the same postcure in air.

This nitrogen postcuring process seems to involve further crosslinking of the polymeric resin and thus accounts for the observed improvements in high-temperature properties and  $T_g$ . But the increased crosslinking can slightly lower room-temperature mechanical properties relative to those obtained with the corresponding air postcure. Long-term (up to 800 hr) nitrogen postcuring of these laminates did not produce any appreciable difference in their room-temperature mechanical properties (flexural and interlaminar shear strength).

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*Nitrogen treatment increases glass transition temperature of PMR-15*

## Structural Mechanics

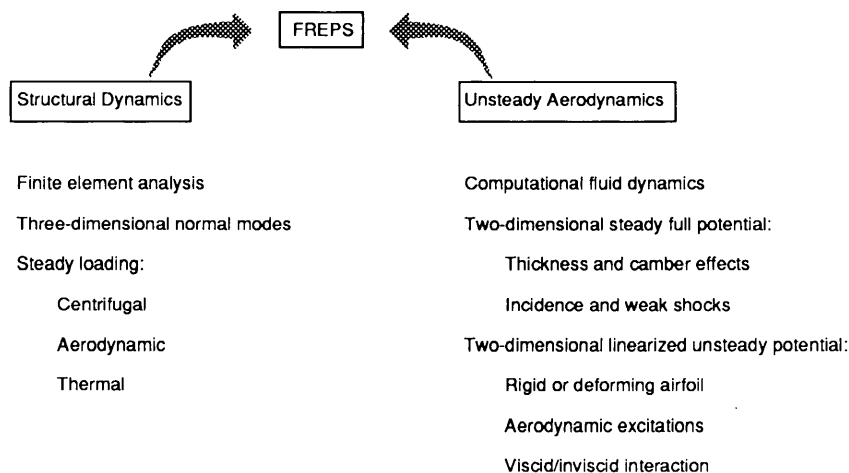
### Turbine Blade Forced-Response Prediction System

High vibratory stresses from forced excitations often are suspected of causing fatigue cracking and early failure in turbine blading of high-energy turbomachinery. An example of this is the shorter-than-expected life of the turbine blades in the space shuttle main engine turbopump. Presently, no aeroelastic analysis can predict the vibratory stresses in such blading. Research is under way at NASA Lewis to provide such an analysis for more reliable design of turbomachinery turbine blading.

A forced-response prediction system (FREPS) is being formed with structural dynamic and unsteady aerodynamic modules. The unsteady aerodynamic module is the key component of the FREPS system. It is being developed under NASA Lewis contract by the United Technologies Research Center. This module permits the rapid calculation of the complex, unsteady flow conditions within cascaded blade passages of turbines with thick and highly cambered airfoil geometries. Two-dimensional, linearized unsteady potential flow theory is being used. Unsteady aerodynamic forces caused by blade vibration (motion dependent) and by other sources, such as wakes and pressure waves (motion independent), are simulated by the analysis.

The structural dynamic module uses a modal approach to represent the blade structure. The natural blade modes are calculated under steady engine operating conditions (i.e., thermal, centrifugal, and steady aerodynamic loading) by using the MARC finite element program.

The FREPS program development is



*Turbine forced-response prediction system*

being coordinated so that the structural dynamic module is developed in parallel with the unsteady aerodynamic module. In addition, an experimental program is planned to verify the accuracy of the FREPS analysis.

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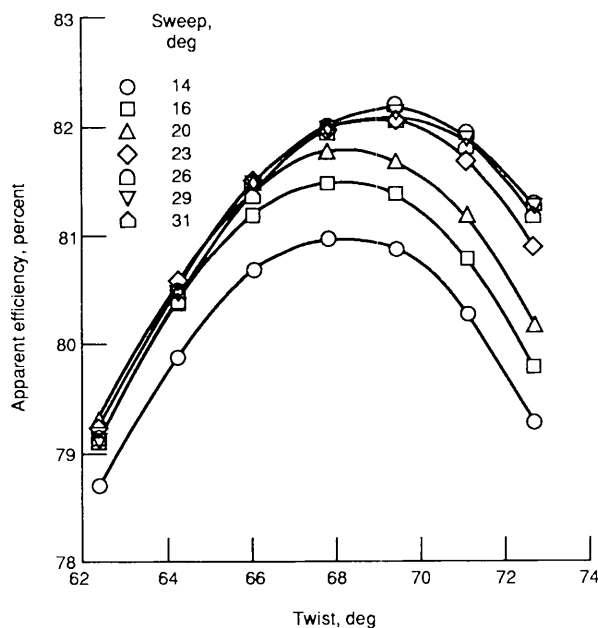
Headquarters program office: OAST

## Parametric Studies of Advanced Turboprops

Development of feasible advanced turboprop blades has traditionally involved a process of repeating trial configurations. Specifically, a swept and twisted turboprop blade would be developed based on advantageous aerodynamic characteristics (including high efficiency and low noise), and then it would be considered for structural analysis. However, blades of this type (thin and highly swept and twisted) exhibit a complex state of structural response under a centrifugal forcefield. Often, as a result, aerodynamically desirable blades were not structurally feasible. This conflict necessitated the development of new blade configurations with the previous structural limitations kept in mind. However, relatively few blade configurations (fewer than eight) have been developed and investigated, and it is not known exactly how the structural limitations of each configuration may be related.

Research was conducted to investigate the effects of sweep and twist upon the structural response of turboprop configurations with acceptable (within a range) aerodynamic efficiency under a centrifugal force field. A representative advanced turboprop was used as a model on which variations of sweep and twist were made. An aerodynamic propeller performance computer code was used to establish and arrange turboprop blade configurations with acceptable aerodynamic efficiency. The array contains blades with seven different sweeps and seven different twists for a total of 49 combinations.

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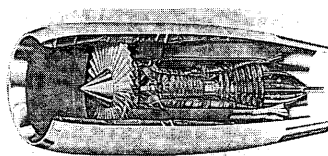
*Effect of twist on apparent efficiency for lines of constant sweep*

## Engine Structures Computational Simulator

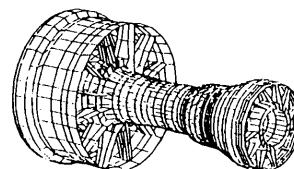
In recent years an escalating number of analytical tools have been developed to aid the engineer in the design and analysis of engine components and systems. Analytical tools available or currently under development include techniques to evaluate environmental operating conditions, fluid structures interaction, structural response, and aeroelastic behavior and to predict life. A growing number of optimization schemes are also under development. As more and more analytical tools are introduced, it becomes increasingly necessary to incorporate them into an integrated design facility.

NASA Lewis is currently developing an integrated multidisciplinary design and optimization facility called the engine structures computational simulator (ESCS). This facility will allow Lewis to assess and fully exploit the large number of analytical tools under development and to conduct research on advanced engineering concepts. Such a facility would allow the aerospace community to produce improved designs more rapidly, with a higher degree of accuracy, at a lower cost.

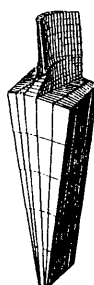
The ESCS system acts as a shell between the user and the large collection of analytical tools available within the facility. The user interacts with ESCS through easy-to-follow, user-friendly prompts and popup menus. A critical requirement of an integrated design system is an efficiently organized means of handling and maintaining the massive amounts of data required by the system. ESCS overcomes this difficulty through the use of a data base management facility developed



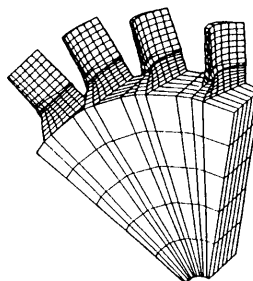
**ENGINE**



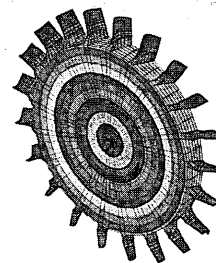
**FINITE ELEMENT MODEL**



**BLADE**



**ROTOR SECTOR**



**ROTOR STAGE**

*Engine structures computational simulator*

at NASA Lewis. The user can view, interpret, or modify the large amount of data at any time in the design process through the use of the data base manager and a robust graphical display facility also developed at NASA Lewis specifically for a workstation environment. Future efforts include an emphasis on the implementation of optimization techniques and multidisciplinary analysis capabilities.

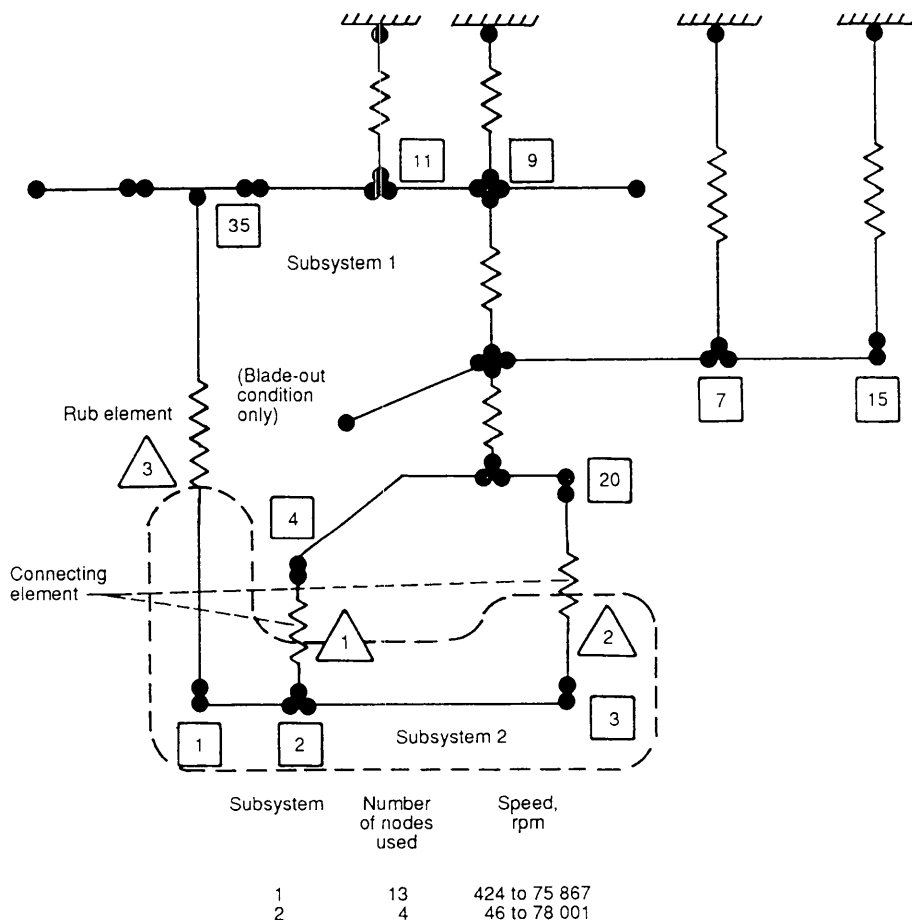
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## Turbine Engine Transient and Steady-State Analysis

In the NASA Lewis-sponsored Turbine Engine Transient Analysis (TETRA) Program, a computational tool was developed to predict the transient dynamic response of engineering structures to suddenly applied loads, such as from the loss of a blade. This tool was improved by adding two modules: the flexible-bladed disk and the squeeze film bearing. The latter was added by Case Western Reserve University under NASA Lewis sponsorship.

In order to synthesize the model, the dynamic response of a complex structure was constructed in terms of the natural modes of its principal structural components. The equations of motion in the modal generalized coordinates were solved numerically by central difference integration in the time domain. This solution has the flexibility to accommodate nonlinearities, such as tip rubs, squeeze films, or other nonlinear bearings or connecting elements. In addition, the gyroscopic coupling between motions in the vertical and horizontal planes of rotating structures is considered for rigid-bladed as well as flexible-bladed disks.

The transient response of a structure is a history of its motions and loads, which initially vary nonuniformly in time until a steady-state condition is reached. Where damping is low and modal frequencies are high, the time steps required to reach steady state can be numerous. For this reason the development of a more direct method to calculate steady-state response was undertaken.



*TETRA schematic of blade-out test vehicle*

Steady-state capability allows the forced-response amplitudes to be calculated as a function of excitation frequency.

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## Development of Hypersonic Engine Seals

High-temperature seals are required to seal structural panel joints and interfaces of advanced variable-geometry hypersonic engines. The seals must prevent extremely hot (5000 °F maximum) high-pressure (140 psi maximum) engine flow-path gases, including unburned hydrogen, from escaping past the movable engine panels. Leakage of these hot flow-path gases could severely damage the engine panel articulation systems and cause catastrophic loss of the engine and the vehicle. Several panel-edge seals showing promise of sealing the interfaces between movable engine side walls and stationary engine splitter walls have been developed

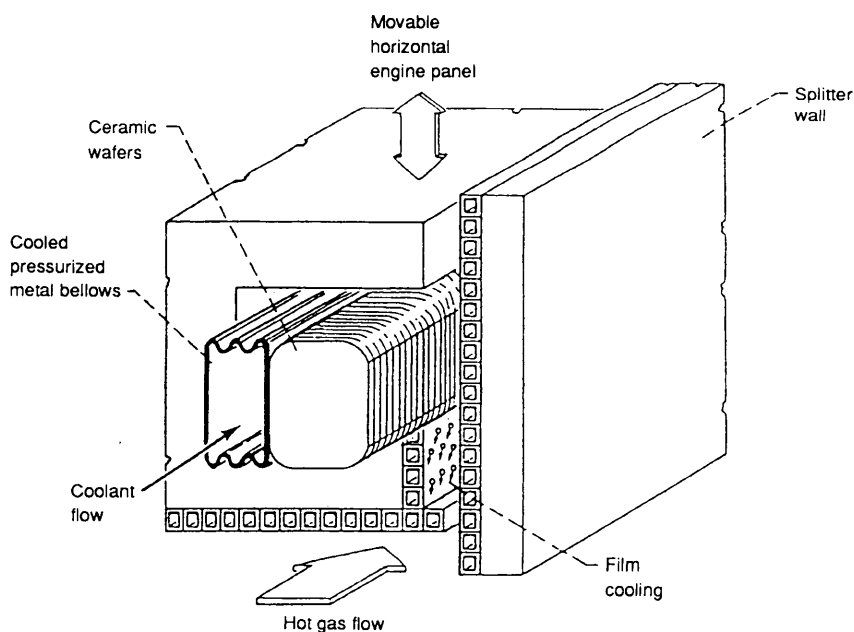
Materials for these seals were selected for their excellent ability to operate at high temperatures (2300 °F) and thus minimize required coolants and for their stability in the chemically hostile hydrogen-oxygen environment. The ceramic-wafer seal is made of stacked ceramic wafers mounted in a seal channel along the edge of the movable engine panel. The seal conforms to engine wall distortions by the relative sliding of adjacent wafers. The ceramic-wafer/ceramic-sleeve seal was constructed by inserting the ceramic wafers in a flexible ceramic sleeve braided of alumina-boria-silicate yarns. The multiple-ply ceramic-sleeve seal is constructed of several braided ceramic sleeves tightly stretched over one another to form a densely packed ceramic rope. The ceramic-ball/ceramic-sleeve seal consists of a braided ceramic sleeve internally packed with small ceramic balls. The ceramic balls easily roll over one another, allowing the seal to conform to both localized engine

wall irregularities and global engine wall distortions. All of the seals except the ceramic-ball/ceramic-sleeve seal meet the tentative maximum leakage criterion for many combinations of applied seal pressure differential and seal preload.

An analytical seal leakage model was developed for the ceramic-wafer seal that relates seal leakage flow rate to gas pressure, temperature, and viscosity and to seal size, length, and apparent leakage gap. The model allows seal designers to estimate the seal leakage flow rate for engine gas mixtures, pressures, and temperatures.

High-temperature friction and durability tests of a flexible ceramic fabric, alumina-boria-silicate (Nextel), were conducted in a pin-on-disk machine. Application of thin solid lubricant films such as silver/calcium fluoride or gold to the fabric reduced friction coefficients by 50 percent and minimized fabric damage when the fabric was heated from room temperature to 1560 °F.

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*Hypersonic engine ceramic-wafer seal*

## Propfan Aeroelastic Response With Mistuning in Off-Axis Flow

An experiment was performed to investigate the effects of frequency and mode shape mistuning on the aeroelastic response of two propfan model rotors. Mistuning refers to the property differences that exist between rotor blades. If rotor blades are identical, all the blades will theoretically have the same aeroelastic response amplitudes. The experiment showed that both inherent mistuning and intentional alternate mistuning significantly affect the response of the blade vibratory amplitudes. Therefore, mistuning should be included in propfan aeroelastic response analyses for reliable blade design.

Two propfan research models, the SR3C-X2 and the SR3C-3 (hereinafter referred to as -X2 and -3, respectively), were used for the experiment. The models had the same geometry (each 2 ft in diameter) and material but differed in natural frequencies and mode shapes. These differences were designed into the blades by varying the ply orientations of the laminated composite blade material.

Blade vibratory strain amplitudes were compared for three rotor configurations. One rotor had all -X2 blades, another had all -3 blades, and a third had both -X2 and -3 blades arranged in an alternating pattern. The -X2 and -3 uniform rotors had inherent mistuning from manufacturing differences of the blades, and the mixed rotor was intentionally mistuned. The vibratory blade excitation was obtained by tilting the rotor shaft in the free stream to obtain off-axis flow into the rotor. This resulted in a dominant excitation and blade

response at a frequency of once per revolution, referred to as 1P.

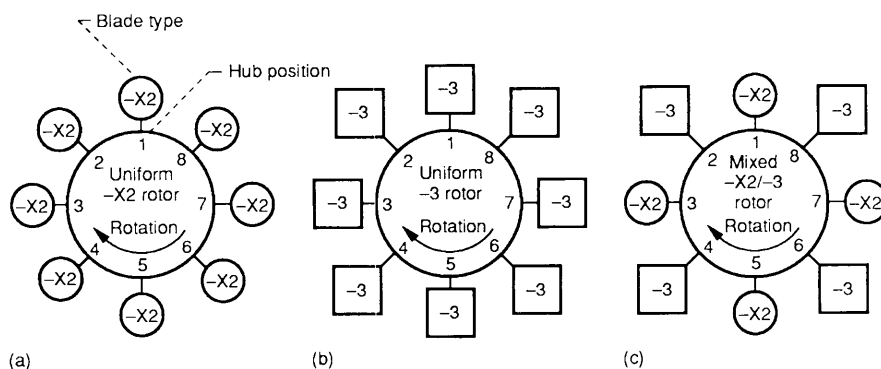
The 1P strain amplitudes of the uniform -X2 rotor were much larger in magnitude and variation than those of the uniform -3 rotor. However, in the mixed rotor the amplitudes of the -X2 blades dropped significantly and were below those of the -3 blades, but the -3 blades had relatively small changes in amplitude relative to the blades of the uniform -3 rotor. Therefore, the intentional alternate mistuning was beneficial, since it caused a large reduction in the 1P amplitudes of the higher responding -X2 blades but a relatively small

change in the 1P amplitudes of the lower responding -3 blades. If only a few blades in the -X2 rotor had been monitored, the maximum responding blades may have been missed; also, the order of variation of -X2 blade amplitudes could not have been predicted intuitively.

### Bibliography

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Uniform and mixed rotor configurations (views looking downstream):  
(a) uniform SR3C-X2 rotor, (b) uniform SR3C-3 rotor, (c) mixed rotor



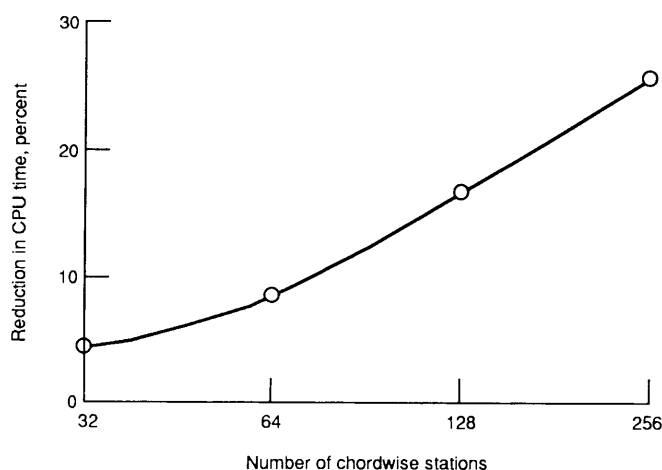
### Semianalytical Technique for Sensitivity Analysis of Unsteady Aerodynamic Computations

The computation of derivatives of response quantities to design parameters, known as sensitivity analysis, plays an important role in developing reliable and efficient procedures for design optimization of practical aerospace structures. The sensitivity derivatives may also be useful in devising computational schemes for aeroelastic analysis and in computing the derivatives of the flutter Mach number and the flutter frequency.

These sensitivity derivatives can be calculated by using a straightforward finite-difference approach. However, experience in other engineering disciplines suggests that a semi-analytical approach may prove to be more computationally efficient. A semianalytical sensitivity analysis was made of the subsonic unsteady aerodynamics used in flutter analysis, so that the derivatives of the generalized unsteady aerodynamic forces could be computed. As a first step, only non-shape-dependent variables representing the flow condition and the structural motion were considered.

The semianalytical approach to the sensitivity analysis of a response function consists of analytically differentiating the original function with respect to an intermediate function and evaluating this derivative by numerical differentiation. The semianalytical approach combines the efficiency of the analytical approach with the ease of implementing the finite-difference approach.

Using the semianalytical approach, we showed that the sensitivity of the generalized aerodynamic force is



*Saving of computer time as function of number of chordwise stations*

equal to the generalized force acting on the blade resulting from a "pseudopressure differential" across the blade surface. The pseudo-pressure differential was shown to be equal to the pressure distribution that gives rise to a "pseudo-upwash" distribution.

The semianalytical approach was applied to two unsteady aerodynamic models: an isolated airfoil in two-dimensional flow and rotating propfan blades in three-dimensional flow. The efficiency of the semianalytical approach relative to the finite difference approach increased rapidly with the number of chordwise stations. This savings in computer time can be significant

when aeroelastically optimizing propfan blades that employ mistuning and a large number of panels with three-dimensional unsteady cascade aerodynamics.

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**Lewis contacts:** Dr. Durbha V. Murthy, (216) 433-6714; and George L. Steffen, (216) 433-3920

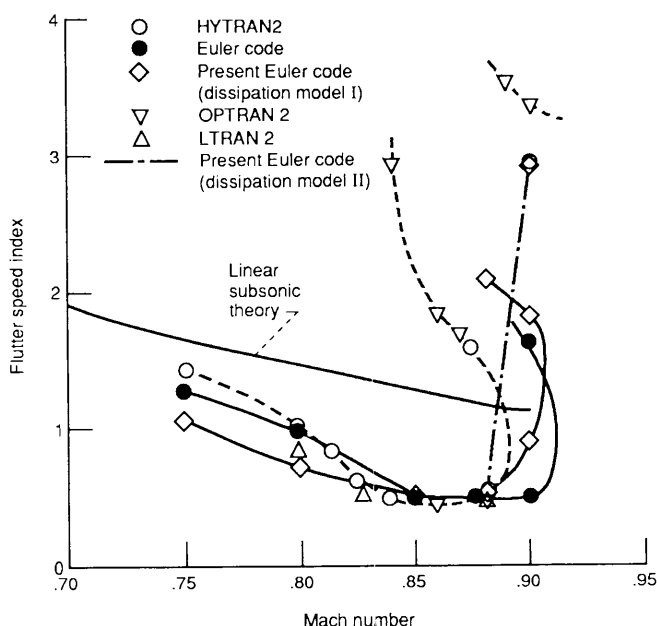
Headquarters program office: OAST

## Rotational Flow, Viscosity, Thickness, and Shape Effects on Transonic Flutter Dip

The transonic flutter dip phenomenon associated with blade sweep on thin airfoils for propfan blades was investigated by using an integrated two-dimensional Euler/Navier-Stokes code and a two-degree-of-freedom, typical-section structural model. The Euler/Navier-Stokes code solves the unsteady, two-dimensional, Reynolds-averaged, compressible, full Navier-Stokes equations on a body-fitted coordinate system in a strong conservation form by using an alternating-direction implicit procedure. An algebraic eddy viscosity model was included to analyze turbulent flows.

The flutter boundary for the NACA 64A010 airfoil was obtained with the Euler version of the code by using two dissipation models. Both model I, based on the local pressure gradient scaled by a common factor, and model II, based on the local pressure gradient scaled by a spectral radius, predicted the same flutter boundary except in the recovery region. There model I predicted a flutter boundary that folds over to provide upper boundaries. No such folding over the boundary was observed when model II was used. Although the recovery portion of the flutter boundary was dependent on the dissipation model, the minima of the dip was unaffected by the model.

The flutter boundary obtained by using the Euler version of the code and dissipation model I was compared with published results. Between Mach 0.70 and 0.82 the flutter speeds predicted by the present Euler code were lower than those predicted by transonic small disturbance (TSD) codes. However, between Mach 0.82



Flutter boundaries for NACA 64A010 airfoil

and 0.87 the flutter speeds were in good agreement.

This behavior can be explained by inspecting the shock location on the airfoil. For example, at Mach 0.80, the shock is near the midchord, indicating rotational flow over a reasonably large area. The TSD theories, unable to model the effect of rotational flow downstream of the shock, predict a higher flutter boundary than does the present code. As the Mach number increases, the shock travels toward the trailing edge and the strength of the shock increases. Between Mach 0.85 and 0.88 the shock is near the trailing edge, thereby reducing the area over which the flow is rotational. Therefore, the Euler code shows the same accuracy as the TSD codes. Beyond Mach 0.88 the shock strength is sufficiently high to induce separa-

tion. The Euler and TSD codes both fail to model separated flow behind shocks and thus predict qualitatively the same flutter boundary beyond Mach 0.88. Parallel studies showed that the effects of mean angle of attack, initial conditions, and viscosity on the flutter boundary are negligible on the minima of the dip but significant away from the dip.

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## Unsteady Supersonic Axial-Flow Aerodynamics

A research project to design, build, and conduct experiments on a single-stage supersonic throughflow fan is now under way at NASA Lewis. During the design stage the question of aeroelastic stability arose. Consequently, a computer code was developed to predict the unsteady aerodynamic loading for supersonic axial flow. This code was then incorporated into an existing aeroelastic stability code (MISER2) to perform the analysis.

In this code Lane's equations are used to calculate the unsteady aerodynamic loads. These equations are the result of an extension of a Laplace transform method first proposed by Miles for a single airfoil with wind tunnel wall interference. Lane's formulation considers a two-dimensional cascade with a supersonic leading-edge locus having arbitrary stagger angle (blade leading edges must be ahead of Mach lines) and arbitrary interblade phase angle. The effects of airfoil thickness, camber, and steady-state angle of attack are neglected.

The NASA Lewis blade is much higher in solidity and lower in stagger angle than typical fan stages. However, the airfoil cross section is similar to that of conventional fan blades. The first mode is primarily bending and the second mode is primarily torsion. The physical properties of the 73.3-percent-span location were chosen as being representative and were used in the flutter analysis.

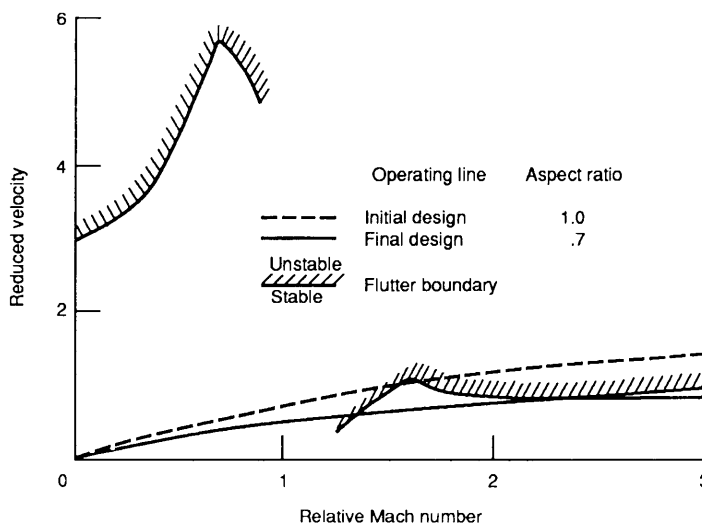
Along with the results for supersonic axial flow, some comparative results were obtained for subsonic axial flow by using other theories (Rao and

Jones, Adamczyk, and Goldstein). For supersonic Mach numbers less than 1.6 the critical reduced velocity starts at a low value of approximately 0.5 and increases with Mach number to approximately 1.0. For relative Mach numbers greater than 1.6, the critical value is always near 1.0. The aeroelastic stability analysis predicted that the blades would be unstable at supersonic relative velocities. As a result the rotor blades were redesigned by reducing the aspect ratio to bring the throughflow fan into the stable operating range.

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*Aeroelastic analysis of supersonic throughflow fan torsional flutter*

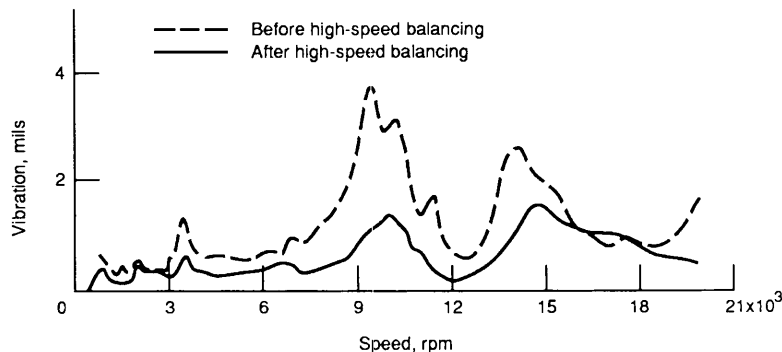
## High-Speed Balancing on a Helicopter Engine

This contract effort comprised three separate tasks: (1) analysis and demonstration of high-speed balancing on a T700 power turbine module, (2) analysis of high-speed balancing on T700 gas generator modules, and (3) development of vibration diagnostics for T53, T55, and T700 engines.

Both the gas generator and the power turbine of the T700 engine operate above bending critical speeds. Close tolerances in manufacture and assembly, combined with careful low-speed balancing, allow satisfactory operation of the engine. The Army was concerned, however, that the close tolerances would be difficult to maintain through engine overhaul. Use of high-speed balancing would allow a relaxation of tolerances (thus lowering cost) and at the same time produce smoother-running engines.

The T700 power turbine assembly was balanced at 20,000 rpm (its normal operating speed) by applying balancing corrections at three locations along the shaft axis. The components of this power turbine had previously been balanced at low speed; the assembly was considered within production tolerances. The vibration was reduced considerably by high-speed balancing, both at the critical speeds and at operating speed. Analysis shows similar benefits for T700 gas generator assemblies.

To assist in repair of overhauled engines that vibrate excessively, vibration spectra were measured for operating conditions used in the acceptance test. Vibration peaks were observed at speeds of the



*T700 power turbine vibration displacement probe*

power turbine (NP), accessory gearbox, 0.89 NG (source unknown), gas generator (NG), and 2AG. Vibration spectra of engines undergoing acceptance tests are compared with the typical spectra. Particularly high vibration at any one frequency indicates a problem in the component producing that frequency. For example, high vibration at NP would indicate an out-of-balance power turbine. With this knowledge, only the component at fault needs to be reworked, rather

than the entire engine as was previously the case. This results in considerable savings of time and resources.

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## Active Control of Rotor Vibrations

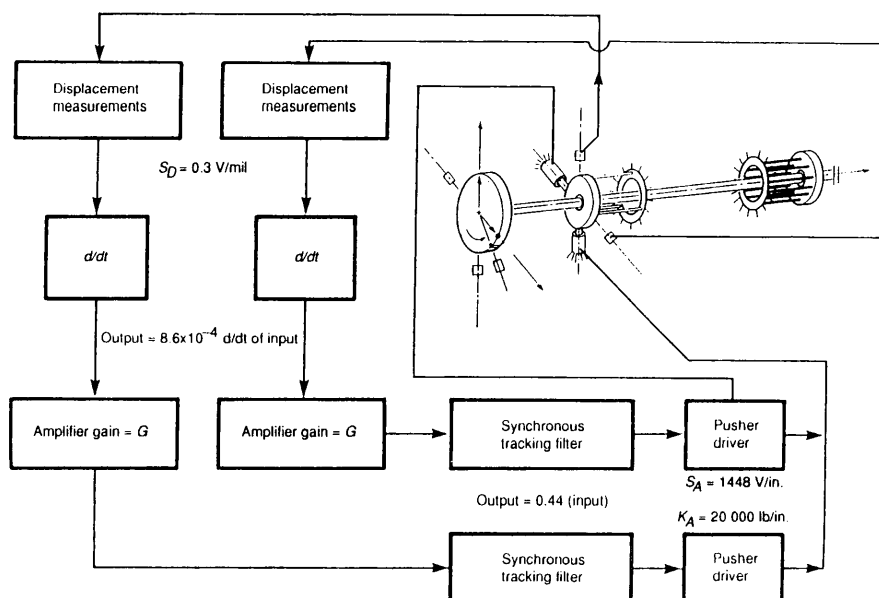
Jet engine shaft vibrations often are suppressed by passive devices such as squeeze film dampers. Research is being performed to replace or supplement these with active dampers in order to reduce engine weight and produce more predictable and reliable damping. Piezoelectric pushers have been tested as actuators in active dampers because of their light weight, compactness, and low voltage. This research showed that standard control theories such as optimal, pole placement, and velocity feedback could be applied to the prescribed displacement characteristics of piezoactuators. Also, the piezoactuators could yield between 50- and 80-(lb sec)/in. damping as determined by comparison of test

and simulation results. A narrow bandpass tracking filter was required to suppress instabilities of the control system. The method was effective except when the rotor speed was just below a critical speed, in which case an instability occurred.

Piezoelectric pusher specifications (force, stroke, and stiffness) required for effective control of vibration in various jet engines were determined by computer simulation. Rotor-dynamics simulations were performed on the T700, T64, and T55 engines. The T700 is a small general aviation engine. The T700 results indicate a requirement for an active damper value of 100 (lb sec)/in., which

produces a pusher internal displacement of 8 mils/(oz in.) and a force of 200 lb/(oz in.). Although the pusher displacement requirement exceeds the 2- to 3-mil limit of existing pushers, larger displacements can be obtained by stacking pushers in series. Similar simulations are currently being performed on the T64 and T55 engines.

The problem of identifying electro-mechanical instabilities arose when the test rig response had high-frequency pulses. Those instabilities ranged from 1000 to 9000 Hz and were caused by the phase change in the differentiators and the piezoelectric pushers. If the total phase lag became greater than  $90^\circ$ , the active damping became negative and an instability could occur. Insertion of low-pass filters into the feedback loop was not a certain solution, since they also have phase lag. A narrow-bandpass, synchronous tracking filter stabilized the system except when the rotor speed approached a critical speed, in which case the  $90^\circ$  phase shift of the filter caused the critical speed to become unstable. The current strategy being developed is to use a combined approach of low-pass filtering, phase-lead circuitry, mechanical natural-frequency shifting, and mechanical isolation to stabilize the closed-loop system.



*Rotor test rig with active damping feedback loop using piezoelectric pusher actuators*

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# Internal Computational Fluid Mechanics

## Numerical Predictions of Flutter for Supersonic Flow Through Cascade Sections

Recently, interest has arisen in designing a turbine engine that operates with supersonic axial flow through the rotor and stator blade rows. Much research is needed to ensure stable operation of this type of design. Understanding the aeroelastic behavior and identifying the flutter boundaries are critical. Many existing structural and aerodynamic analysis methods are based on flat-plate theory and introduce approximations to model thickness and blade camber. One alternative is to use a finite difference algorithm to predict the flowfield and account for these effects.

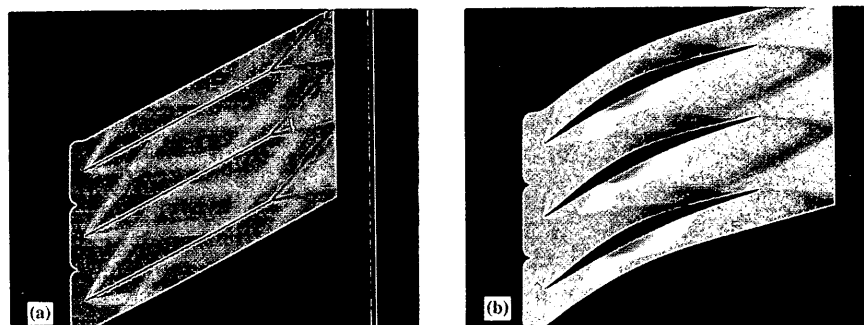
A nonlinear, two-dimensional compressible Euler code has been developed at NASA Lewis for modeling supersonic flow through oscillating cascades. The code uses a deforming grid technique to capture the blade motion in the cascade. Solutions for any arbitrary interblade phase angle can be found by modeling the flow around only three blades of the cascade. The resulting large reduction in computational requirements is an important feature for a designer performing an aeroelastic analysis.

This code is an extension of the NS2D3 code developed in 1988 by NASA Lewis for modeling unsteady, transonic flow through oscillating cascades. The current version of the code was completed in January 1989 to aid in flutter analysis of the supersonic throughflow fan being researched at NASA Lewis. Comparisons have been done with small-perturbation theory for a flat-plate cascade. To date, this is the

only validation tool available, since experimental data for oscillating cascades in this flow regime do not exist. Results show very good agreement for both the unsteady pressure distributions and the integrated force predictions. Sample predictions have been made for a section of the rotor from the supersonic throughflow compressor design. Preliminary results indicate that two-dimensional, flat-plate analysis predicts conservative flutter boundaries. Therefore, modeling "real" blade sections is important for the accurate prediction of the unsteady flowfield needed for aeroelastic analysis.

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*Static pressure contours for supersonic flow through an oscillating cascade: (a) flat-plate cascade, (b) midspan section from supersonic throughflow rotor design*

## Cooled-Turbine Heat Transfer and Flow Modeling

Although increasing the turbine inlet temperature is a lucrative approach to improving the specific thrust and thermal efficiency of gas turbines, available materials limit the turbine inlet temperature of uncooled turbines to about 1800 °F. Blades must be cooled to achieve significantly higher turbine inlet temperatures. Typical internal cooling passages of modern gas turbines may have ribbed turbulators, pin fins, finned passages, leading-edge impingement, bypass flows, lateral ejection, 180° turns, and flow branching.

A generalized cooling passage flow analysis code has been developed to facilitate evaluating the effects of these cooling passage designs on the thermal analysis of the rotor disk and blades. The code solves the compressible one-dimensional mass, momentum, and energy equations. Rotational effects (Coriolis and buoyancy effects) are incorporated in a quasi-two-dimensional manner. The code can compute the mass flow in the main branch and the sub-branches (if any) and the pressure, temperature, heat transfer coefficient, and wall heat flux distribution in the coolant passage. The code predictions have been compared with a wide variety of nonrotating and rotating passage experimental data representing various types and combinations of cooling passages. The code predictions agree well with the experimental data.

This code has been incorporated in an automated thermal analysis procedure developed for cooled turbines (only radial turbines at present). This procedure has been applied to compute the three-

dimensional temperature distribution in the rotor disk and the blading of a cooled radial research turbine to be tested at NASA Lewis. Future work will involve conducting experiments on the cooled radial turbine to obtain the heat transfer data and to validate the analysis procedure. A three-dimensional viscous analysis of the coolant passage flow is also under way.

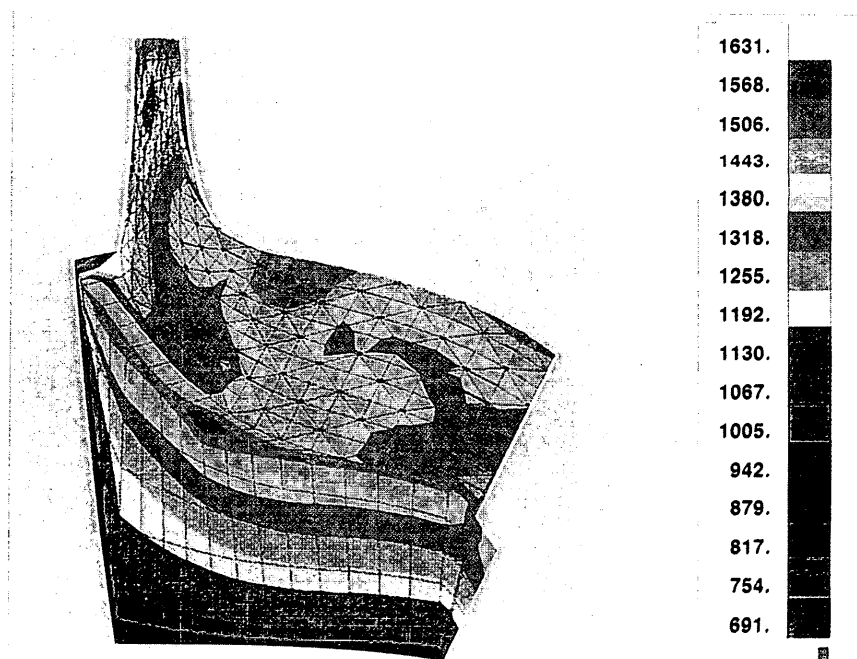
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Kumar, G.N.; Roelke, R.J.; and Meitner, P.L.: A Generalized Computer Code for Turbomachinery Cooling Passage Flow Calculations. AIAA Paper 89-2574, July 1989. (Also NASA TM-102079.)

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*Thermal analysis of cooled radial turbine*

## Cycle Simulation Code for High-Mach-Number Turbine Engines

NASA Lewis has as one of its primary functions the analysis and evaluation of advanced aircraft propulsion systems. Since 1975, steady-state thermodynamic engine cycle performance has been calculated with the NNEP computer code. This code was a joint development between Lewis and the Naval Air Development Center and is widely used in Government agencies, commercial companies, and universities.

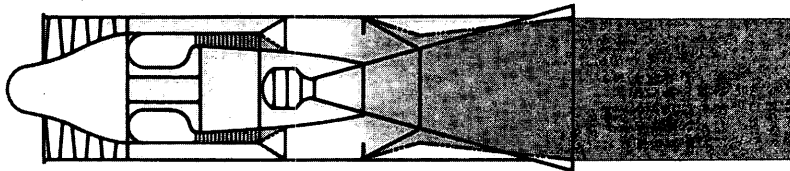
Recently, there has been an increased interest in studying engines that the NNEP is not capable of simulating: very high-Mach-number applications, alternative fuels including cryogenics, cycles such as the gas-generator air turborocket, and cycles employing ejectors such as those for short takeoff and vertical landing (STOVL) military fighters. New engine component models were created for incorporation into NNEP, as was the capability to include chemical dissociation effects of high-temperature (above 2200 °R) gases. As a result, a new version of the code, called NNEPEQ, has been developed and made available to the user community. This work was accomplished through a combination of in-house and contract (S. Gordon & Associates) efforts.

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*Air turborocket*



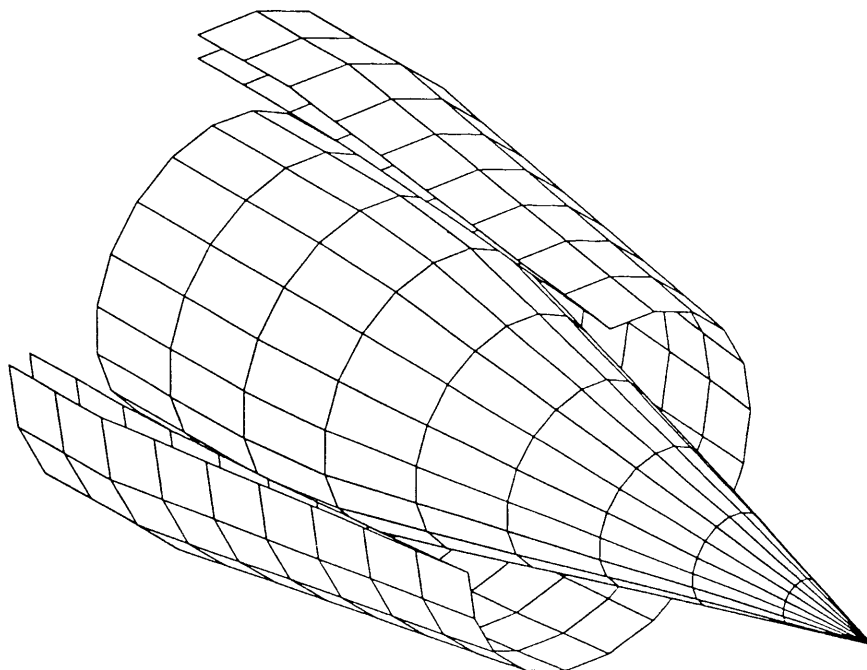


## Preliminary Design of Supersonic Inlets

With renewed interest in sustained supersonic cruise vehicles the need has arisen at NASA Lewis to assess many new potential propulsion systems for this application. One of the key components for a successful propulsion system is the inlet. The operating efficiencies and the size, weight, and complexity of supersonic inlets can profoundly affect the ability of a given propulsion system to meet the requirements of a supersonic cruise mission. In an effort to better model the contributions of inlet operation on the propulsion system as a whole, a preliminary design and performance prediction methodology has been developed.

The methodology targets supersonic inlets for cruise at Mach 2 to 5. Geometric design may be accomplished by using a method-of-characteristics design program. Another method-of-characteristics analysis program may then be applied to assess the internal supersonic flowfield over a wide range of supersonic operating conditions.

An inlet performance analysis code (IPAC) was developed to predict the performance of the selected inlet geometry over the entire operating range from takeoff to cruise. The program is capable of analyzing pitot, axisymmetric, or two-dimensional inlets. Total pressure recoveries, airflows, aerodynamic drags, and structural weights are calculated. The aerodynamic drags computed include spillage, bleed, bypass, and cowl lip wave drags. The program can also produce plots of inlet performance and performance maps used in engine cycle and mission analysis programs. This effort was performed by Sverdrup Technology, Inc.



*Supersonic inlet*

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## Multiarchitecture Parallel-Processing Testbed for Computational Fluid Mechanics

Current research in the parallel processing of computational fluid mechanics applications indicates that the architecture of parallel processors can significantly affect the performance of algorithms. NASA Lewis is investigating architecture-algorithm interactions through the use of a multiarchitecture testbed called the hypercluster, conceived and developed in house. Researchers can investigate the performance of algorithms by using any of a number of subset architectures of the hypercluster, or the entire hypercluster itself. The hypercluster structure offers maximum flexibility for exploiting several levels of parallelism within a single algorithm. The hypercluster will be used as a tool in developing and testing parallel-processing strategies for numerical simulations and for processing data from physical experiments.

The hypercluster supplements the distributed-memory architecture of a hypercube with shared-memory clusters of processors (scalar or vector) at each hypercube node. Thus, the hypercluster can provide both tight coupling (within a shared-memory node) and loose coupling (between nodes) of processors. A four-node prototype of the hypercluster is operational. Each node presently contains four commercially available, board-level microcomputers. The hypercluster can be expanded by adding more nodes, more processors per node, or both.

Users interact with the hypercluster through a host computer. A first generation of hypercluster system software has been developed to assist

users in interactively programming and executing applications on the hypercluster. This includes a new library of parallel-processing routines that allow programmers to access hypercluster communication services from Fortran programs. HYCLOPS, the first-generation operating system for the hypercluster, provides for interactive loading and execution of application programs, display and modification of memory contents during execution, and retrieval of output data.

Hypercluster hardware and software are being tested and validated by using two-dimensional heat convection and Navier-Stokes flow solver codes. Preliminary results have been obtained by running the two-dimensional Navier-Stokes flow solver on a single, shared-memory node with one, two, and three scalar processors. Speedups of 1.60 and 2.29 were obtained with two and three processors, respectively, over the single-processor version. More highly parallel versions of this code, combining vector, shared-memory, and distributed-memory parallel processing, are being developed and will demonstrate the full capabilities of the hypercluster.

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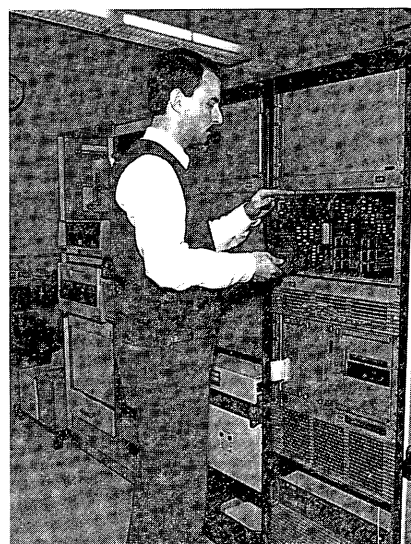
Blech, R.A.; Quealy, A.; and Cole, G.L.: A Message-Passing Kernel for the Hypercluster Parallel-Processing Test Bed. Proceedings of the Fourth Conference on Hypercubes, Concurrent Computers, and Applications, Monterey, CA, March 6-8, 1989. (Also NASA TM-101952.)

Cole, G.L.; Blech, R.A.; and Quealy, A.: Initial Operating Capability for the Hypercluster Parallel-Processing Test Bed. Proceedings of the Fourth Conference on Hypercubes, Concurrent Computers, and Applications, Monterey, CA, March 6-8, 1989. (Also NASA TM-101953.)

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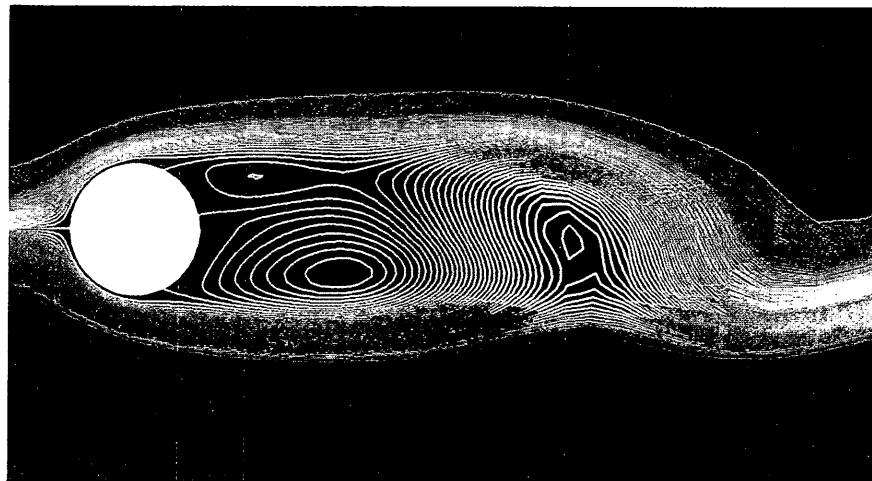
Microcomputer board being inserted in hypercluster system

## Navier-Stokes Code for Aerospace Propulsion Applications

An effort is currently under way at NASA Lewis to develop two- and three-dimensional Navier-Stokes codes called PROTEUS for aerospace propulsion applications. These codes are expected to support the National Aerospace Plane (NASP), Space Shuttle Main Engine (SSME), Integrated High-Performance Turbine Engine Technology (IHPTET), and National Propulsion System Simulator (NPSS) Programs, as well as generic research in inlets, nozzles, and turbomachinery. Both Lewis and Sverdrup Technology support service personnel are involved. The support service personnel are being funded by the NASP and SSME programs.

The emphasis in the development of PROTEUS is not algorithm development or research on numerical methods, but rather the development of the codes themselves. The objective is to develop codes that are user oriented, easily modified, and extensively documented. Code readability, modularity, and documentation (both internal and external) have been emphasized. Version 1.0 of the two-dimensional planar/axisymmetric code has recently been released. The three-dimensional version is scheduled for release within the next one to two years.

PROTEUS solves the Reynolds-averaged, unsteady, compressible Navier-Stokes equations in strong conservation law form. Turbulence is modeled by using a Baldwin-Lomax-based algebraic eddy viscosity model. The governing equations are written in Cartesian coordinates and transformed into generalized nonorthogonal body-fitted coordinates. They are solved by marching in time using a fully coupled alternating-



*Computer results for low-Mach-number laminar flow past a circular cylinder at a Reynolds number of 100 (based on diameter)*

direction-implicit (ADI) solution procedure with generalized beam-warming first- or second-order time differencing. The boundary conditions are also treated implicitly and may be steady or unsteady. All terms, including the diffusion terms, are linearized by using second-order Taylor series expansions.

In addition to solving the full set of Reynolds-averaged equations, options are available to solve the thin-layer or Euler equations and to eliminate the energy equation by assuming constant stagnation enthalpy. Artificial viscosity is used to minimize the odd-even decoupling resulting from the use of central spatial differencing for the convective terms and to control pre- and postshock oscillations in supersonic flow. Two artificial viscosity models are available—a combination implicit/explicit constant coefficient model and an explicit nonlinear coefficient model designed specifically for flows with shock waves. At NASA Lewis the code is normally run on the

Cray X/MP computer and is highly vectorized.

An extensive series of validation cases have been run, primarily using the two-dimensional planar/axisymmetric version of the code. Several flows were computed for which exact solutions to the Navier-Stokes equations exist, including developing channel and pipe flow, Couette flow with and without a pressure gradient, unsteady Couette flow formation, flow near a suddenly accelerated flat plate, flow between concentric rotating cylinders, and flow near a rotating disk. Additional validation cases that have been successfully run include driven cavity flow, boundary layers with confined separation, normal and oblique shock-boundary layer interactions, converging-diverging nozzle flow with an unsteady terminal shock, and flow past an airfoil.

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## Multistage Compressor Flow Physics

Future civil and military aircraft will require continued advancements in propulsion system technology. A key component of the propulsion system is the compressor, and the continued drive for reductions in engine fuel burn, the move to supersonic flight speeds, and the need to increase thrust-to-weight ratio will lead to compressor technology demands far beyond current capabilities and far beyond the ability of current design methods.

In order to provide the advanced technology required for these future compression systems, NASA Lewis has begun a Multistage Compressor Flow Physics Program that features a tightly coupled effort between computational, experimental, instrumentation, and high-speed-computing research areas. The computational effort is centered on the average-passage multistage analysis method. An important element of the development of this method involves the formulation and assessment of the appropriate closure models. The experimental element of the program is directed toward providing measurements that will be used to guide the development of these closure models and to validate Navier-Stokes computational methods for rotors and stators.

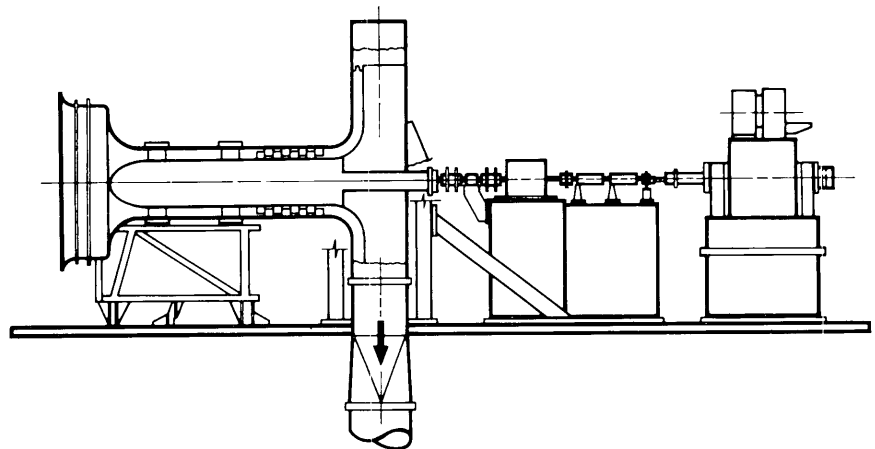
The experimental research will be conducted in both high-speed and low-speed compressors. The high-speed research, focused on the measurement of thermodynamic properties through the compressor, will be conducted in existing Lewis facilities. The low-speed research will be performed on a new low-speed multistage axial compressor currently under development. The four-stage

axial compressor research package is 4 ft in diameter and rotates at 950 rpm. The large size and low speed of the compressor result in the proper Reynolds number, minimal blockage effects associated with intrusive instrumentation, and an endwall boundary layer thick enough to facilitate detailed endwall region measurements. In addition to measurements made with conventional intrusive techniques, laser anemometry and other advanced measurement techniques developed as part of the instrumentation research element of the program will be used.

Detailed mechanical design and fabrication of long-lead-time items for the facility are currently under way. Experimental research is planned to begin in 1991.

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*Low-speed, multistage, axial-flow compressor*

### Inverse Design Code for Automated Turbomachinery Airfoils

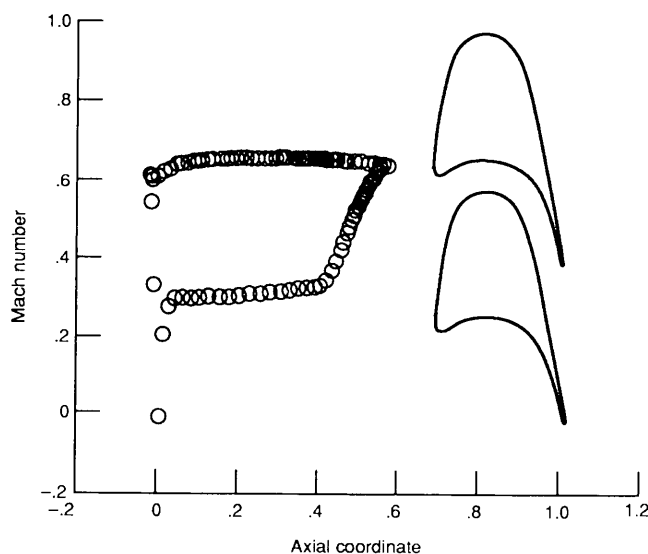
A set of sample cases has been produced to test an automated procedure developed at NASA Lewis for the design of controlled diffusion blades. The project's main objective was to document the automated design procedure's range of application. Characteristic compressor and turbine blade sections were produced with the automated design code, and various other airfoils were produced with the base design method before the automated procedure was incorporated. Sample cases were proposed by a number of engine manufacturers.

The design code has proven to be an excellent source of innovative designs. Experimental results for some of these designs have been obtained at the NASA Ames Research Center and the Thermal Sciences and Propulsion Center of Purdue University as well as here at Lewis. The code was used in the past to design a unique vane set for the Ames 40- by 80- by 120-Foot Wind Tunnel. Various other designs have been described elsewhere, and an extensive comparison with analysis codes is presented in the literature. More recently, a report being published by AGARD, "Test Cases for Computation of Internal Flows in Aero Engine Components," includes two of these designs.

The code uses approximately 200K words of memory, and a typical design can be accomplished within 5 to 10 min on the Cray X/MP.

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*Automated design of turbomachinery airfoils*

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## **Development of Three-Dimensional, Steady, Turbomachinery Code**

NASA Lewis is conducting research to develop the computational capability for analyzing steady flows in turbomachinery components; to support programs of advanced turbomachinery design at NASA, at the Department of Defense, and in the aeropropulsion industry by providing validated computer codes; and to develop and implement new numerical techniques to improve the accuracy, robustness, efficiency, and application of the codes.

A general three-dimensional steady Navier-Stokes code for rotating blades has been completed, and an appropriate three-dimensional grid generation package has been developed. The code has been applied to studying a three-dimensional horseshoe vortex near the endwall. The code has also been supplied to support a project for analyzing the aerodynamic characteristics of supersonic throughflow fans. Computation has been carried out on a Cray X/MP supercomputer—a typical run for a three-dimensional computation on 0.1 million grid points requiring approximately 1 hour. Current and future efforts specifically involve upgrading the capability of the code in the following areas: (1) incorporate a multigrid strategy to improve the efficiency of the code, (2) develop a capability to analyze the effect of tip clearances, (3) develop unsteady analysis for wake-blade row interaction and rotor-stator interaction, and (4) improve turbulence models for predicting heat transfer on turbine blades.

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## Interactive Grid for Flow Simulations in Propulsion Components

A family of menu-driven interactive grid generation programs (TURBO) is being developed to generate grids for aircraft propulsion components: TurboT for turbomachinery and TurboI for nozzles, ducts, and inlets. These interactive programs use a sparse collection of control points from which the shape and position of coordinate curves can easily be adjusted. A distinct advantage of these programs over other grid generation programs is that they allow the easy change of local mesh structure. The TURBO programs can thus achieve a balance between the constraints of the internal flow passages and the grid structures required to obtain accurate flow simulations.

In the sample case shown here for illustration, TurboT first constructed an initial control net for a compressor rotor and then computed an initial grid by using the control-point form of algebraic grid generation. The highly skewed initial grid was then changed to the much more orthogonal modified grid by changing the initial control net to the modified control net. Operation of TurboT only requires use of the workstation mouse and selection of TurboT menus.

Developing TURBO is a joint effort between NASA Lewis and Columbia University. Before the end of 1989, two-dimensional TURBO programs will reach a certain level of maturity. At that time a single-block, three-dimensional version of TURBO will exist in a basic form. Some parts of the three-dimensional version have been established. These include the overall mathematical

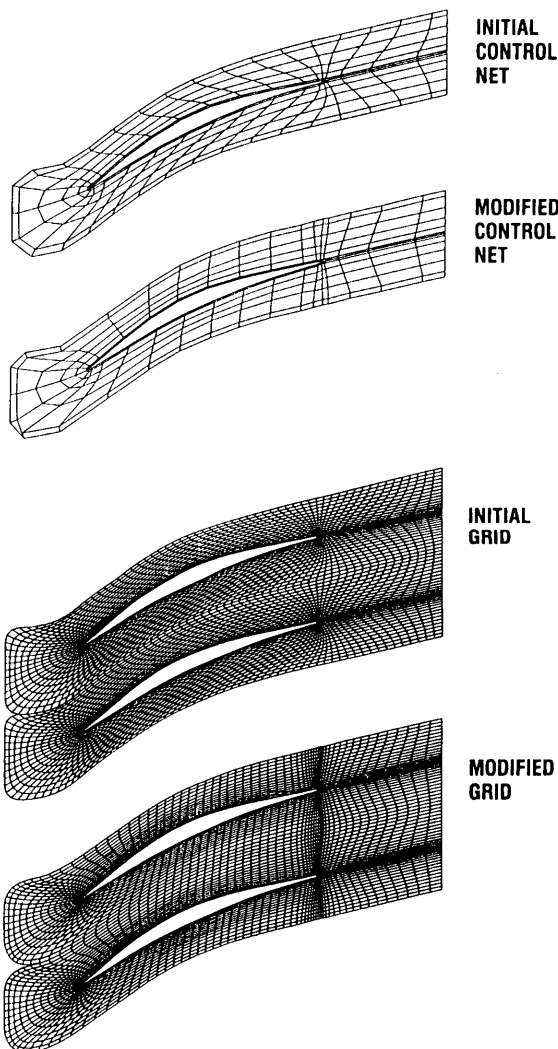
structure, the coding of local  $C^2$  blending functions, and the template for the program assembly. All TURBO programs run on IRIS workstations.

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*Interactive grid generation for a compressor rotor (TURBO program)*

## Analysis of Hypersonic Scramjet Module Gap Seals

Previous efforts to investigate the aerodynamically induced thermal loads in and around scramjet module gap seals have relied upon simple one-dimensional models. This gap seal is crucial in the development of the scramjet concept, since the seal must prevent extremely high-temperature and -pressure gases from leaking through the junction of the articulating cowl and the stationary splitter plate. In-house efforts are under way to characterize the highly three-dimensional and highly interactive flowfield in and around the gap seal by using a NASA Lewis-modified three-dimensional Navier-Stokes solver. Lewis has improved the efficiency and robustness of the code by adding a new algorithm (LU-SGS, or lower-upper symmetric Gauss-Seidel) as well as its accuracy in computing high-enthalpy flows by including efficient real-gas aerothermodynamics. This three-dimensional flowfield prediction capability based on Navier-Stokes technology has been used to aid structural dynamicists in understanding gap seal aerothermodynamics.

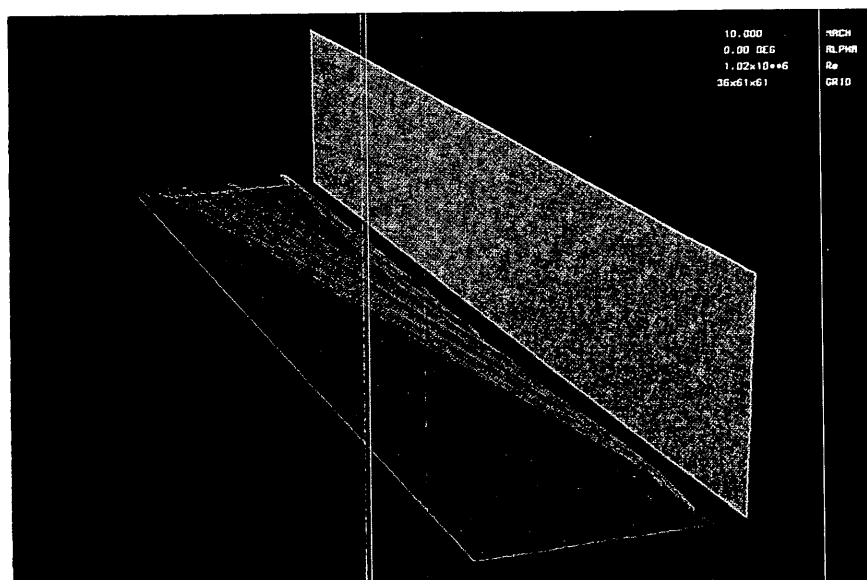
Calculations to date have simulated the scramjet module gap seal environment at a flight Mach number of 10 and an altitude of 100,000 ft. Gap fluid expulsion and mixing resulted in a vortical structure located along the seal apex. The expulsion of the gap seal fluid lowered the heat transfer rate to the seal floor. The vortical structure appeared to act as a barrier, preventing the more energetic outer flow from entering the seal area. Future work will address the effect of seal aspect ratio on overall gap seal performance as well as investigate the effect of inert gas blowby

from the seal floor. The calculations were all performed on the Langley Cray Y/MP.

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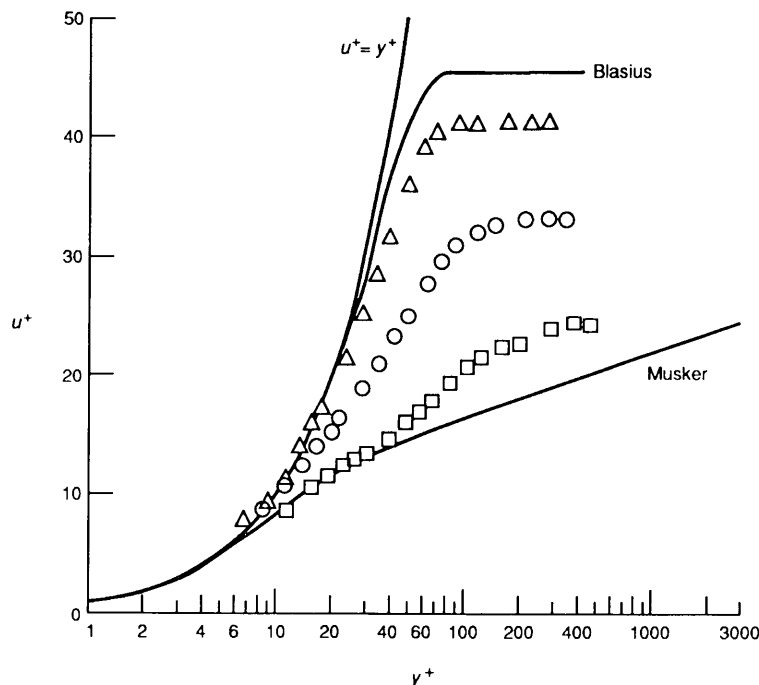
Particle traces in hypersonic scramjet module gap seal



## Heat Transfer in Transitioning Boundary Layers

Heat transfer rates from cooled turbine airfoils are strongly influenced by the state of the boundary layer adjacent to the blade surface. Turbulent boundary layers yield significantly higher heat transfer rates than laminar. Consequently, the ability to predict the location and length of boundary layer transition on the airfoils is an important consideration to the design engineer. Parameters that influence transition onset and extent include turbulence level, streamwise pressure gradient, and surface curvature. All of these factors are present on turbine airfoils. Turbulence levels are high owing to the high levels of mixing in the combustor. High levels of turbulence promote early transition. Negative streamwise pressure gradients are caused by flow acceleration through the blade passages. Negative pressure gradients are a stabilizing influence and thus delay transition. The net result of these effects is that transitional flow often occurs over a relatively long length along the airfoil chord. The goal of this in-house research program is to provide an improved predictive capability for transition onset and length and for heat transfer rates in the transition zone.

Boundary layer transition experiments are being carried out in a closed-loop wind tunnel in which the free-stream turbulence level and the streamwise pressure gradient can be controlled. The floor of the tunnel is uniformly heated and serves as the test surface. Tunnel qualification measurements of surface heat transfer and boundary layer velocity and temperature profiles yielded excellent agreement with literature correlations. Bypass-mode transition



*Representative conditionally sampled mean velocity profile  
(Reynolds number, 507,000)*

has been documented at high free-stream turbulence levels. This mode of transition does not include the selective amplification of initially small (linear) disturbances as predicted by linear stability theory.

The transitional boundary layer is intermittent, characterized by intervals of laminar flow followed by intervals of turbulent flow in a quasi-random fashion. Conditional sampling was used in the transitioning boundary layer in order to distinguish between laminar and turbulent intervals and to allow for determination of separate statistics for these intervals. Future measurements of two components of velocity plus temperature will be made with a miniature custom three-wire probe.

Conditional sampling will also be applied in this case, allowing for determination of Reynolds stress and turbulent heat flux for the turbulent intervals of the intermittent boundary layer.

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## Instrumentation & Controls

### Calibration of Droplet-Sizing Instruments for Aircraft Icing Research

Characterizing icing clouds is important in aircraft icing research as researchers strive to more accurately model ice formation on aircraft, to design icing protection devices, and to improve the safety of winter flights. Icing clouds are studied in wind tunnels with tunnel-mounted instruments and in the atmosphere from heavily instrumented research aircraft.

Knowing the size distribution of water droplets in icing clouds is important in this research. Today, measurement of droplets in icing clouds is usually based either on their light-scattering properties or on their light-blocking properties. Particle size may be deduced from the amount of laser light scattered from the droplet within a certain range of viewing angles. Particle size may also be derived from the size of the shadow cast on an array of photodetectors. However, these laser-based optical particle-sizing measurements have suffered from uncertainties due to incomplete knowledge of instrument operating envelopes and to the lack of reliable calibration standards.

NASA Lewis has developed new calibration devices for these instruments because there is no known way to repeatably create a droplet cloud with a known size distribution. Use of these devices has significantly increased confidence in the measurement data and has resulted in a more complete and reliable definition of the operating envelopes for the instruments. The NASA Lewis calibration devices have allowed checking the health and calibration of these instruments installed in a

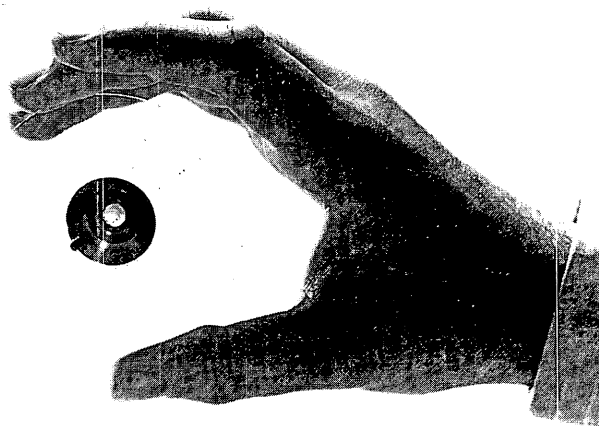
*Rotating reticle calibration device*

tunnel or on a grounded icing research plane.

For the instruments using the light scattered from droplets the calibration device consists of a rotating pinhole placed in the focused laser beam of the instrument. The light diffracted by the pinhole provides a stable and repeatable pattern of light intensity to the optical detectors in the instrument, thus simulating a droplet of known size. The velocity of the simulated droplet may be varied by changing the speed of rotation; however, the size remains well known and fixed.

For instruments using the droplet shadow the calibration device is a rotating reticle. The reticle consists of a glass substrate with micrometer-sized chromium disks deposited on its surface. These disks, which serve as particle simulators, are used to verify instrument health and to adjust the calibration of the instrument. This rotating reticle is becoming generally accepted as the calibration

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device of choice for these instruments and is commercially available.

In order to define the operating envelope of these instruments, factors affecting their accuracy and health must be discovered and quantified. For these instruments factors of interest include instrument alignment, condition of the instrument optics, droplet flow-path obstruction, droplet number density, and droplet velocity. At NASA Lewis these factors have been investigated through the use of computer simulations, analytical calculations, laboratory testing, and comparisons between different instruments in wind tunnel tests.

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## Combustion

### Enhanced Jet Mixing

Effective mixing of flow streams is necessary for the efficient operation of several propulsion system components. Examples include mixing of a hot engine exhaust jet with the surrounding cooler air for engine exhaust temperature reduction, mixing of the fuel and air within a combustor, and mixing of turbine exhaust and ambient air within an ejector nozzle. In each of these cases, it is desirable to achieve the required mixing in as short a length as possible in order to minimize both the surface area and weight of the mixing component.

A research program at NASA Lewis is investigating methods for enhancing the mixing process and thereby reducing the mixing length between two flow streams. The enhancement is achieved through application of a small-amplitude, unsteady excitation velocity. The source of the excitation velocity in the Lewis experiments is a sophisticated acoustic speaker system with controllable frequency and amplitude. The underlying principle of the technique involves using the excitation velocity produced by the speakers to enhance and regularize the development of the large-scale vortical structures that naturally develop as part of the mixing process between two streams. These regular and larger amplitude large-scale structures are much more effective at mixing the two streams than the smaller scale, random structure (turbulence) that also develops within the mixing layer.

Experimental results have demonstrated significant increases in mixing effectiveness for round jets exiting into ambient air. Initial experiments involved applying the excitation velocity at a single

frequency corresponding to the preferred development frequency of the large-scale structures within the round jet mixing layer. More recent experiments have demonstrated an added benefit to the mixing process by applying the excitation velocity simultaneously at two frequencies: the first corresponding to the mixing layer preferred frequency, and the second to half that value. Excitation at this second frequency combines the large-scale vortical structures into even larger structures for an additional increase in mixing effectiveness.

Experiments are currently under way to examine the effect of applying the excitation velocity at more than two frequencies and also with various modal characteristics. Facility modifications are planned to add a

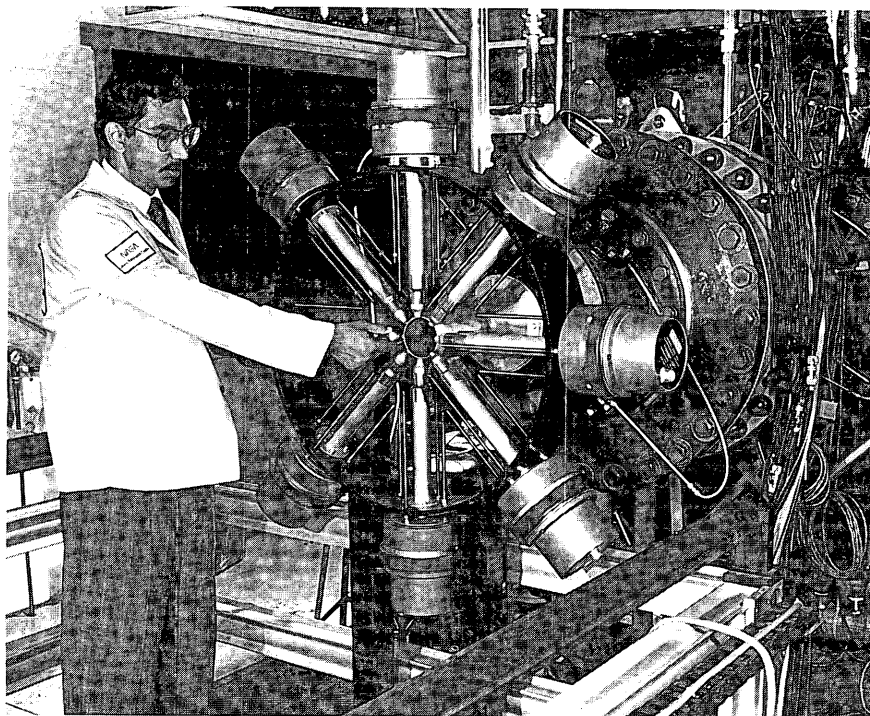
supersonic jet capability. A major objective of the research at supersonic jet velocities will be to explore the feasibility of using these excitation principles to favorably affect the aeroacoustic performance of nozzles for a future high-speed civil transport aircraft.

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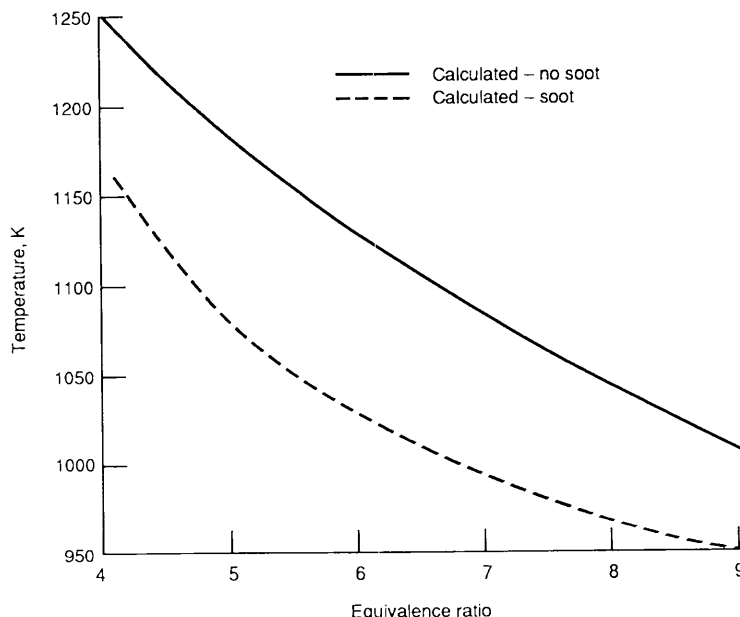
*Acoustic speaker system for enhancing jet mixing*

## Fuel-Rich Catalytic Combustion of Jet A Fuel

Using conventional hydrocarbon fuels for high-speed airbreathing propulsion systems introduces problems of fuel reactivity, combustion stability, and emissions of soot and oxides of nitrogen ( $\text{NO}_x$ ). A method for extending the use of liquid-hydrocarbon fuels for high-Mach-number propulsion systems would obviate the need for cryogenic fuels and the complications involved in aircraft design and the fuel distribution system.

NASA Lewis has developed a method for preprocessing liquid-hydrocarbon fuels in which the fuel (iso-octane or Jet A) is partially reacted with heated air over a catalyst in a flow reactor. The fuel is atomized and prevaporized at mixture ratios of four to eight times the stoichiometric ratio and flowed through a ceramic honeycomb matrix coated with a platinum-iridium catalyst. The original fuel is cracked and partially oxidized on the catalyst surface to produce a gaseous fuel consisting chiefly of lighter hydrocarbons, hydrogen, and carbon monoxide. Temperatures exiting the catalyst are in the range 1100 to 1250 K. The gases produced are completely transparent, since no soot carbon is produced in the process. Calculations using the NASA Lewis chemical equilibrium program agree with the measured temperatures if formation of soot is not allowed in the calculation. Analysis of the products for Jet A fuel accounted for 70 to 90 percent of the fuel carbon in the gas sample, mostly as  $\text{C}_1$ ,  $\text{C}_2$ , and  $\text{C}_3$  molecules; the balance was condensed as a liquid in a cold trap.

With fuel-rich catalytic combustion as the first stage of a two-stage



Measured reaction temperatures for Jet A

combustion system, the cleaner burning and more reactive fuel can be utilized by high-speed engines, where time for ignition and complete combustion is limited, and engines where emission of thermal  $\text{NO}_x$  is critical. Two-stage combustion (rich-lean) has been shown to be effective for  $\text{NO}_x$  reduction in stationary burners where residence times are long enough to burn up any soot formed in the first stage. Such residence times are not available in aircraft engines. Thus, the soot-free nature of the present process is critical for high-speed engines. The estimated maximum temperature of the gases produced from fuel-rich catalytic combustion is probably 1350 K, the threshold temperature for soot formation. The high temperature produced by this process enables the use of fuel-lean combustion in a second stage as a technique

for controlling the combustion temperature and the formation of thermal  $\text{NO}_x$ .

Experiments are currently under way to scale up the process (see "Catalytic Oxidation of Hydrocarbons"), and design has begun for tests of a two-stage burner.

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Lewis contacts: Theodore A. Brabbs, (216) 433-5588; and Erwin A. Lezberg, (216) 433-5884  
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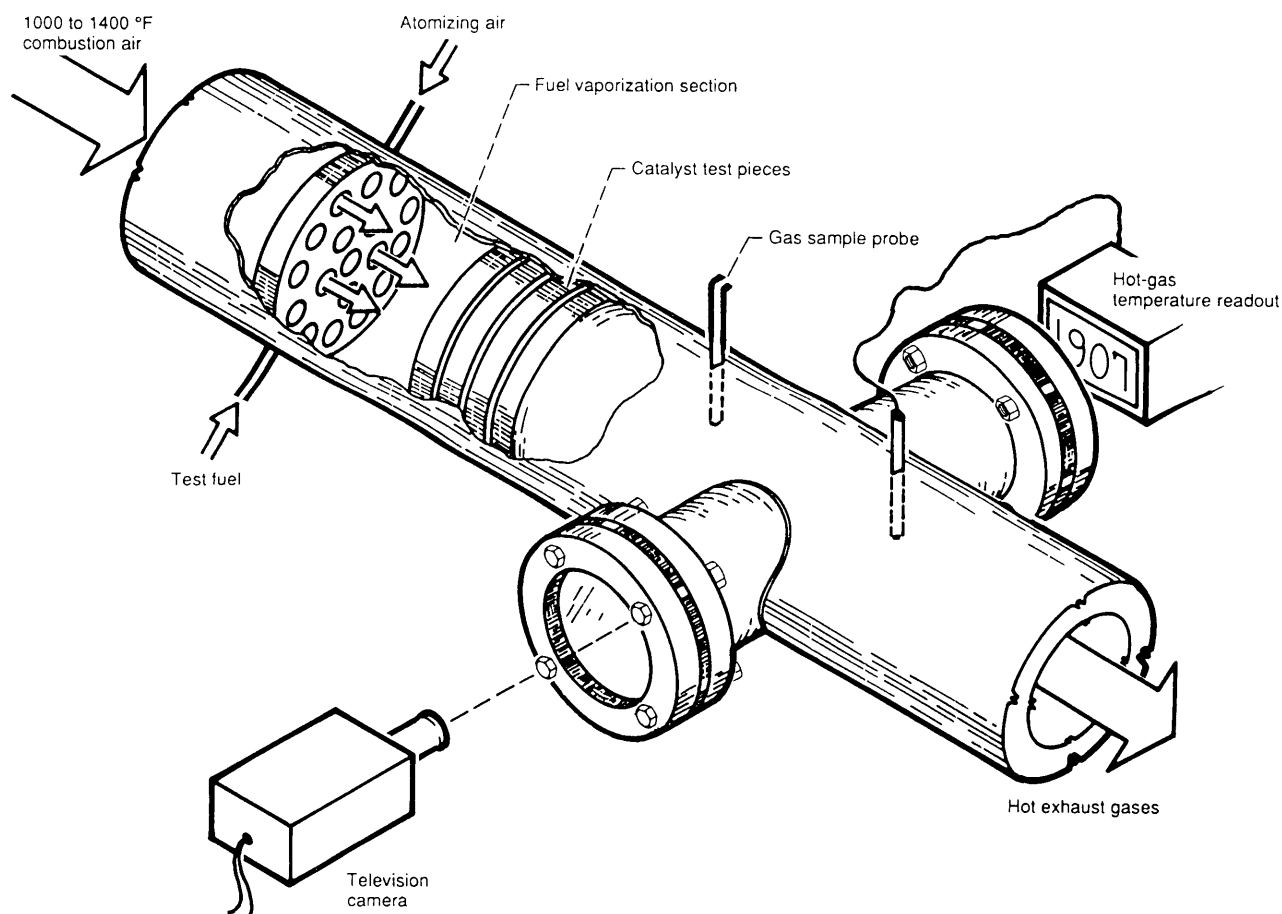
## Catalytic Oxidation of Hydrocarbons

NASA Lewis is conducting an in-house research program to convert liquid Jet A fuel into reactive gas constituents for burning in high-velocity airstreams. The approach is to vaporize the liquid fuel and partially react it catalytically under extremely rich stoichiometric conditions—equivalence ratios of 3 to 9. For comparison, ideal combustion occurs at an equivalence ratio of 1. This research is viewed as providing a noncryogenic fuel alternative for high-speed combustion systems.

To date, experiments have been confined to a single burning stage. Both iso-octane, a single-boiling-point fuel, and Jet A fuel have been investigated. The reactive gas formed consists of carbon monoxide, hydrogen, and unburned light hydrocarbons. Small amounts of carbon dioxide and oxygen, the quantity depending on the equivalence ratio, were also formed. Exhaust gases were shown not to contain any carbon or smoke. The operating temperatures of 1700 to 1950 °F preclude their formation.

Future research will incorporate the catalytic oxidation burning stage into a two-stage combustion system. The second burning stage, incorporating high-velocity air, will be used to complete combustion of the reactive gas.

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*Hot section for testing fuel-rich catalytic reactions*

## Propulsion System Components

### Joint NASA Lewis/Langley Cold-Flow NASP Nozzle Test

High gross-to-net thrust ratios are required for national aerospace plane (NASP) propulsion systems, which are designed primarily for hypersonic flight Mach numbers. A large area ratio is required for optimum performance at hypersonic speeds, but presents a problem at transonic and low supersonic speeds, where highly integrated, typical scarfed nozzle designs are not amenable to much variable geometry. At these lower speeds the nozzle pressure ratios and flows are not adequate to fill the base. Therefore, there is a potential for large areas of separated flow, resulting in high afterbody drags and low thrust-minus-drag performance at the critical transonic condition.

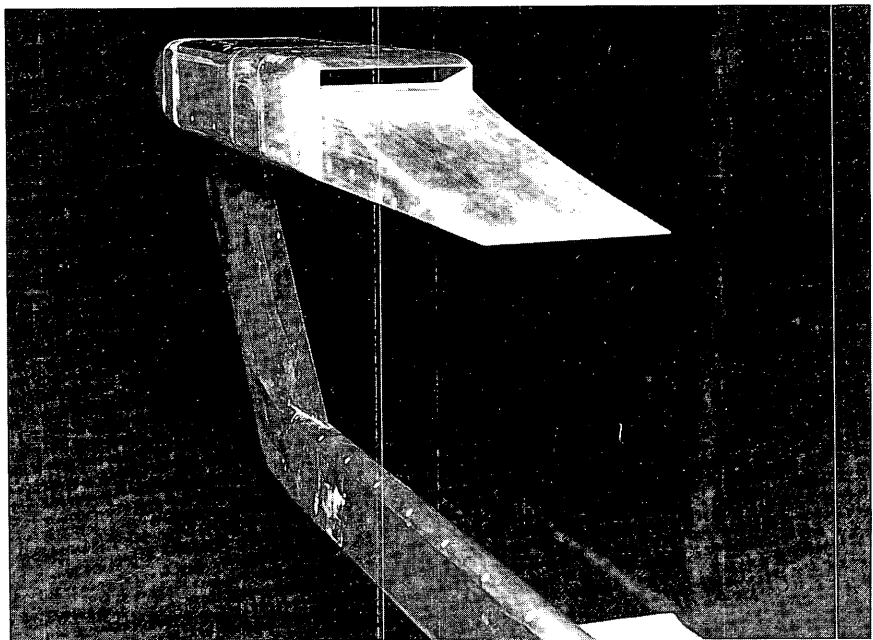
In order to address this issue, a scale-model test program was begun at NASA Langley Research Center in the 16-Foot Transonic Wind Tunnel in 1988. Thrust-minus-drag performance data were obtained by using a cold-flow jet rig with a six-component force balance over a range of test conditions from static to Mach 1.2. This same model was then brought to NASA Lewis and tested in the 10- by 10-Foot Supersonic Wind Tunnel over a range of conditions from Mach 2.0 to 3.5. In these tests a wide range of NASP nozzle configurations were assessed, including NASA designs, Technology Maturation Program configurations, and NASP contractor configurations. Testing began in May 1989 and was completed in July.

This combined test program has provided the first indication of the magnitude of the transonic and low supersonic speed performance problem for the NASP vehicle. Preliminary results indicate that it will be

significant. New methods to improve transonic performance will have to be researched. Included in these methods are mechanical devices to control the flow separations, base burning configurations, and tests with hot nozzle flows. As a result NASA Lewis is proceeding with the design and fabrication of a new jet exit test rig for the wind tunnels that will include hot flow (4000 °R) capability. This test rig will allow the addition of base burning with advanced nozzle configurations.

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*Scale model of NASP nozzle in wind tunnel*

## Supersonic Throughflow Fan

NASA Lewis has embarked on a program of experimental and analytical research to demonstrate supersonic throughflow compression system technology at design and off-design conditions. The aerodynamic design of a supersonic throughflow fan was conducted by using advanced computational codes. The design pressure ratio was 2.45 at a tip speed of 1500 ft/sec. The design inlet Mach number was 2.0. The mechanical design and fabrication of the rotor were completed in 1988 and testing began this year.

Computational fluid dynamics analysis of the supersonic throughflow fan has continued. A three-dimensional, viscous flow solution at the design point has been obtained for the supersonic throughflow fan rotor by using a Navier-Stokes code. Particle traces reveal the three dimensionality of the flowfield in the vicinity of the endwalls and blade surfaces. However, the flowfield outside these regions is highly two dimensional.

Additional testing has been completed in the supersonic throughflow linear cascade at Virginia Polytechnic Institute and State University. The cascade was tested at a nominal inlet Mach number of 2.37 and over a 20° incidence angle range. The chord-wise distribution of the isentropic Mach number on the blade surfaces and the pitchwise distribution of exit Mach number are in good agreement with a two-dimensional solution from a quasi-three-dimensional Navier-Stokes code.

The Supersonic Throughflow Fan Facility became operational during the past year. Before the fan was installed, it was necessary to check out the facility and test package to

determine the flow conditions in the test section. The checkout testing has been completed and the measured flow conditions were in excellent agreement with those from the analysis.

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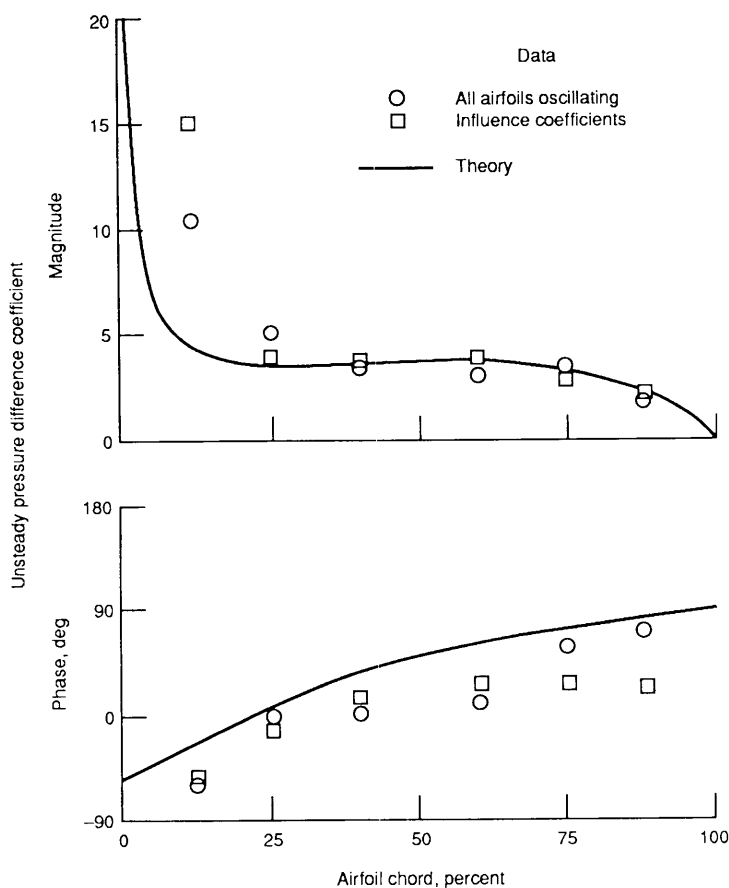
**Headquarters program office:** OAST

## Oscillating Cascade Experiment

The possibility of blade flutter in turbomachines and advanced propellers is a continual concern. The ability to predict flutter has not kept pace with the overall advances and new requirements of turbomachinery and turboprop designs. Consequently, the development of advanced cascade unsteady aerodynamic analyses is a fundamental research interest. Directing this development and evaluating these, as well as existing, analyses, require data from oscillating cascade experiments. However, because of the complexity of these experiments few results are available, particularly in the high subsonic and transonic flow regimes. The NASA Lewis transonic oscillating cascade is dedicated to providing the needed data.

A major feature of this cascade is the high-speed mechanical drive system, which imparts controlled torsional oscillations to the airfoils over a range of interblade phase angles. The cascade is composed of nine biconvex airfoils with a thickness-to-chord ratio of 0.076, a solidity of 1.3, and a stagger angle of  $53^\circ$ . The amplitude of the airfoil motion is  $1.2^\circ$  with a maximum oscillation frequency of 500 Hz, corresponding to a semichord reduced frequency of about 0.5 for high subsonic inlet Mach numbers.

Traditional oscillating cascade experiments are time consuming because for each mean flow condition and reduced frequency of oscillation, the cascade unsteady aerodynamics are required for a number of different interblade phase angles. In order to avoid these problems, oscillating cascade data might be obtained through simpler experiments. In particular, when the unsteady disturb-



*Correlation of theory and experiment for oscillating airfoils*

ances are small, as in many flutter stability problems, an unsteady aerodynamic influence coefficient technique might be used. In this technique, only one airfoil is oscillated, with the resulting airfoil unsteady pressure distributions measured on the oscillating airfoil and its stationary neighbors. The unsteady aerodynamics of an equivalent cascade with all airfoils oscillating at any specified interblade phase angle is then determined through a vector summation of these influence coefficient data.

Verifying this technique requires correlating results obtained by the

influence coefficient technique with data obtained for all of the airfoils oscillating simultaneously. For example, at an inlet Mach number of 0.65, a mean incidence angle of  $7^\circ$ , and a reduced frequency of 0.39, the influence-coefficient-determined, unsteady airfoil, surface pressure difference data were correlated with corresponding experimental data for all the airfoils oscillating in phase. There was good agreement between the two experimental data sets for both magnitude and phase. In addition, the predictions from a linearized flat-plate oscillating cascade theory were plotted. There was good magnitude agreement



except in the leading-edge region, but the predicted phase distribution was offset from the data, possibly because the theory neglects nonuniformities in the mean flow.

Use of the NASA Lewis transonic oscillating cascade to investigate the aerodynamics of oscillating cascades continues; a low-solidity cascade configuration is being used to simulate advanced propeller geometries. Verification of the unsteady aerodynamic influence coefficient technique continues as a part of this program.

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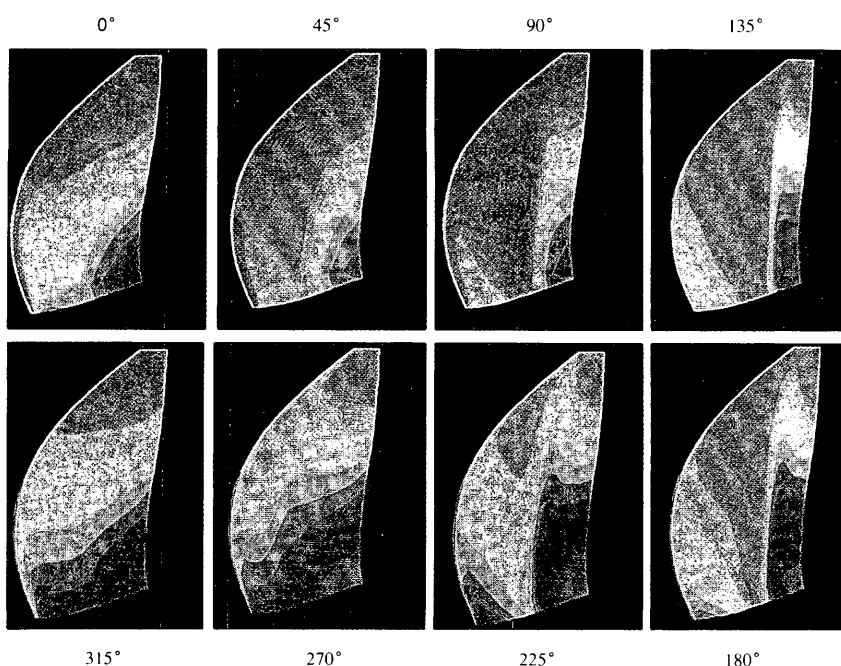
#### Propeller at Angle of Attack

Propellers installed on aircraft operate with the propeller axis at an angle of attack to the flight direction during much of an aircraft's flight profile. This results in time-varying (or unsteady) aerodynamic airloads, which increase both blade material stresses and propeller-generated noise. Accurate prediction of the unsteady airloads is important to ensure blade structural integrity during flight and to allow propeller-powered aircraft to meet Federal noise restrictions at takeoff and landing conditions.

A time-accurate flowfield calculation for an advanced eight-blade propeller at angle of attack has been performed on the Cray X/MP computer at Lewis. The calculation was performed by using a code developed at Mississippi State University under a grant from NASA Lewis. The code

solves the unsteady three-dimensional Euler (inviscid) equations by using a grid-blocking scheme to allow the efficient calculation of the propeller flowfield. The flows in all eight blade passages are solved simultaneously for a total of 206,184 grid points.

Results are shown for the eight-blade SR-7 propeller at Mach 0.80 and a  $4.6^\circ$  angle of attack. Colors represent the instantaneous static pressure levels on the blade. Pressures on the pressure side of the blade are shown. With the propeller nose up,  $90^\circ$  corresponds to the propeller blade at top,  $270^\circ$  to the blade at bottom. At  $0^\circ$ , the blade is moving upward, and at  $180^\circ$  it is moving downward. Peak loading occurs at approximately  $225^\circ$ ; minimum loading at approximately  $45^\circ$ . A quasi-steady aerodynamic



*Blade pressure contours for an advanced propeller at angle of attack*

analysis would indicate peak loading at  $180^\circ$  and minimum loading at  $0^\circ$ . A shock wave from the trailing edge of the suction side of the adjacent blade impinges on the blade (rapid color change from green or yellow to red) at angular locations of  $90^\circ$  to  $270^\circ$ .

These aerodynamic results will be used to predict propeller noise levels measured in flight on the Propeller Test Assessment (PTA) aircraft. This improved definition of instantaneous blade pressures is expected to provide better agreement between predicted and measured values of advanced propeller noise.

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#### **Compact Radial Turbine Rotor**

A highly loaded compact radial rotor that is 40 to 50 percent shorter than conventional radial rotors, but just as efficient, is being investigated under a joint program between NASA Lewis and Pratt & Whitney Aircraft. The program includes the design, analysis, and experimental evaluation of two compact rotors and a baseline conventional rotor. In the past year three stator-compact rotor configurations have been tested in the Lewis Small Warm Turbine Test Facility, and one of the compact rotors was analyzed with a three-dimensional "average passage" viscous code.

Results of the test program have been extremely good for the two rotors evaluated. Tests completed include overall stage performance, cross-span surveys of the flowfield at the nozzle inlet and the rotor exit, and a sector survey of the flow in the nozzle vaneless space. Preliminary evaluation of the test data indicated performance comparable to

that of conventional-length rotors. Analysis of one of the compact rotors with the three-dimensional code is well under way. Three flowfield calculations have been made: an inviscid and two viscous solutions. The viscous solutions were made first without and then with rotor blade clearances. Results of the code computations show good agreement with test data and provide an insight into the flow physics of compact rotors. Further analyses of the test results and refinements in the computational model are continuing.

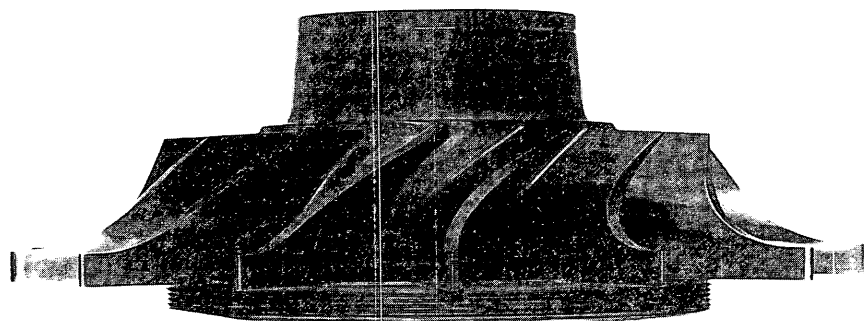
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*Compact radial turbine rotor*

## Ceramic Components for Gas Turbine Engines

In order to exploit the high-temperature performance potential of the gas turbine engine without using strategic materials or exotic hot-section cooling techniques, NASA Lewis is working to develop a ceramic component technology base. As a part of the U.S. Department of Energy's Automotive Gas Turbine Program, the Advanced Turbine Technology Applications Project (ATTAP) is developing structural ceramic hot-flow-path component technology for advanced small gas turbine engines. These engines, designed to operate at temperatures to 2500 °F, have the potential for significantly less fuel consumption than either metal turbine engines or conventional piston engines. In addition, the turbine engines operate with reduced emission levels that meet the current and proposed Federal standards.

Technology development contracts are in place with the Allison Gas Turbine Division of General Motors and with the Garrett Auxiliary Power Division of the Allied-Signal Aerospace Company. Each contract relies on the strong support of the U.S. ceramics industry for component development.

During the past year, 2500 °F turbine stage component designs based on improved ceramic materials were completed. Three-dimensional and probabilistic analyses of both axial and radial turbine stage components were performed. The turbine rotor remains the critical component because of its high temperature, high stress, geometric complexity, and susceptibility to impact damage. Engine test experience has shown the turbine rotor to

be the primary failure site, and impact damage has been identified as a primary rotor failure mode. A combined approach of design and materials properties improvements is being used to increase reliability.

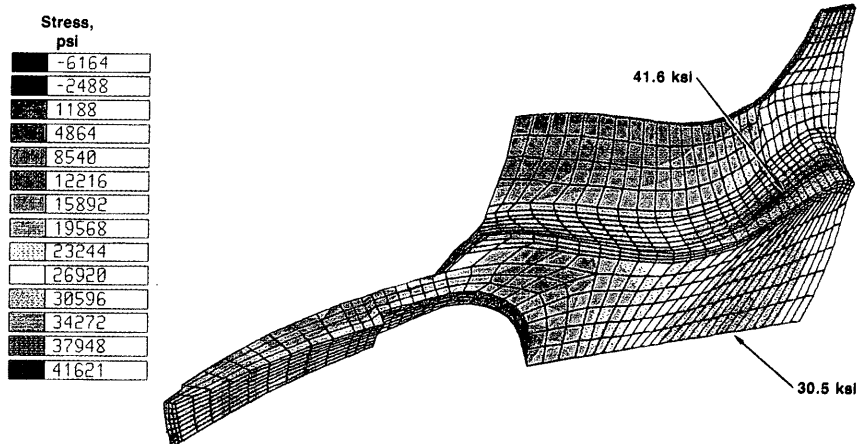
The U.S. ceramics industry has demonstrated on the order of a 50-percent improvement in fracture strength of silicon nitride materials with greatly improved high-temperature chemical stability. Development subcontracts to apply these improved materials to components are currently under way. Fabrication process parameters for injection molding and slip casting of engine components have been established. Manufacture of prototype components to be used for dimensional and property characterization has begun. Engine quality components for hot-rig and testbed engine evaluation are scheduled for delivery in early 1990.

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*Rotor steady-state maximum principal stresses at maximum power*

## Two-Dimensional Inlet and Short Diffuser Testing

As part of the Advanced Short Takeoff and Vertical Landing (ASTOVL) Program, in 1983 NASA Lewis and McDonnell Douglas Aircraft Company tested a 43-percent scale model of the F-15 aircraft inlet in the 9- by 15-Foot Low-Speed Wind Tunnel at Lewis. Test results showed that drooping the inlet cowl lip can substantially improve inlet performance in the low-speed regime. A long, conventional, free-of-separation diffuser was then used for the test. This long diffuser, although providing a good flow quality for the aircraft engine, contributed significantly to the overall inlet gross weight, which can adversely affect the aircraft flight range. In 1987, NASA Lewis began a research program to develop a highly compact short diffuser that would substantially reduce the overall inlet length and weight. However, the new diffuser is predicted to have a highly unstable separated flow in the supersonic inlet operation mode. Therefore, a concept of boundary layer control by slot and discrete nozzle blowing was included in the research and model design. Experimental testing was conducted to determine the short diffuser's performance in the low-speed regime and also the effectiveness of the boundary layer control concept for the high flight Mach numbers.

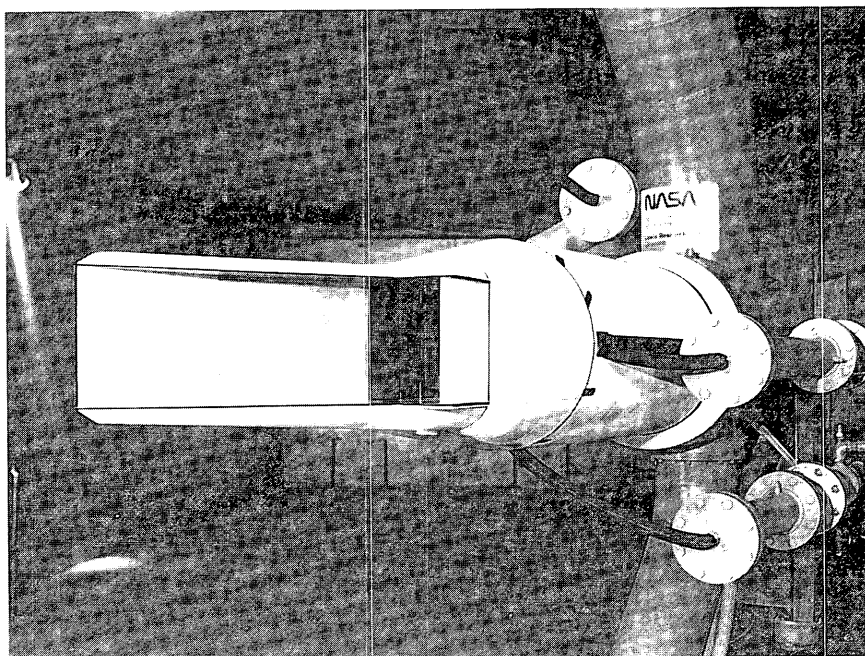
A model of the two-dimensional inlet with the short diffuser was tested in the Lewis 9- by 15-Foot Low-Speed Wind Tunnel in 1989. With the baseline configuration (no cowl lip droop), low-speed test results indicated that the short diffuser produced lower recovery and higher distortion than the long

diffuser. With the inlet cowl lip drooped to 40° and 70°, performance comparable to that of the long diffuser was obtained. Diffuser boundary layer control tests showed that both slot and discrete nozzle blowing can control flow separation. Slot blowing required a lower blowing pressure ratio but more blowing mass flow than discrete nozzle blowing for comparable performance. Results from this test program indicate that a droop lip can give acceptable performance at low flight speeds for a two-dimensional inlet with a short diffuser and that a boundary layer control system can prevent diffuser separation at high flight speeds.

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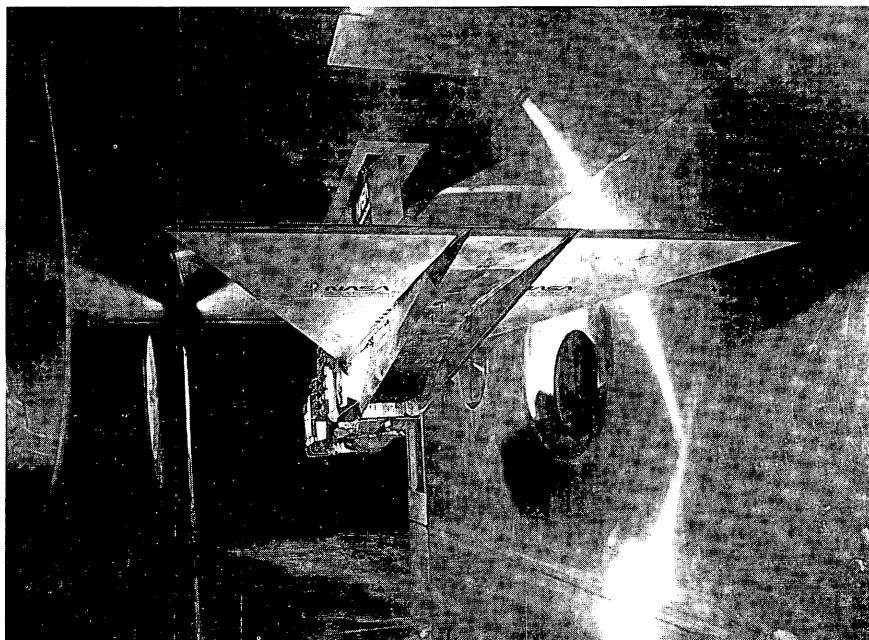
*Scale model of F-15 inlet*

## Mach 5 Inlet Research

During a joint research study, NASA (Lewis and Langley) and industry (Lockheed and Pratt & Whitney) developed a conceptual aircraft capable of sustained cruise at Mach 5. The proposed propulsion system for the aircraft was an "over-under" turbojet plus ramjet. This dual flow system was designed to provide the required propulsion over the entire speed range from 0 to Mach 5. In addition to the airplane design and the evaluation of the performance potential for this class of aircraft, experimental evaluation of propulsion system components that appeared practical from a design viewpoint was begun. Since the data base for inlets at this high-speed cruise condition was practically nonexistent, the inlet was selected for further study.

An experimental research program has been conducted on the inlet system of the Mach 5 aircraft in the NASA Lewis 10- by 10-Foot Supersonic Wind Tunnel. Only the high-speed configuration of the inlet (ramjet), representing operation between Mach 3 and 5, was incorporated into the test model. This inlet was designed by the method of characteristics with boundary layer connection. The large inlet model incorporated a variable-geometry ramp system and remotely variable mass flow plugs for the main duct and bleed airflows. So that Mach 5 conditions could be evaluated in this test facility, which has a maximum Mach number of 3.5, the inlet model was mounted under a large plate and run at negative angle of attack. Thus, the free-stream Mach number of 3.5 was expanded to the desired first-ramp Mach number of 4.1.

Early supporting research studies,



*Mach 5 inlet in wind tunnel*

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using analytical codes and small-scale basic inlet testing in the NASA Lewis 1- by 1-Foot Supersonic Wind Tunnel, indicated that the inlet would have a boundary layer flow migration on the forward sidewall that would result in flow separation just inside the cowl lip. This separation could prevent the inlet from operating in the desired started mode. Therefore, the large-scale inlet, which was instrumented for inlet performance, was also extensively instrumented for computational fluid dynamics validation data on the forward surfaces. Additional bleed

was also added to the inlet on the forward sidewalls and on the cowl near the leading edge. The experimental program was to be accomplished in two phases with the first phase devoted to validation data and only limited overall inlet data. The first phase of the experimental program has been completed. The code validation part of the study was of particular interest for the National Aerospace Plane (NASP) Program, which supported this part of the overall effort.

Inlet data have been obtained for the

Mach 3 to 5 speed range. These data indicate that the expansion concept for acceleration of the tunnel flow performed as predicted. An important data base has been established for validating the complex analytical codes. The data base includes extensive surface static pressure information, along with fixed and translating total pressure probes at several locations. The data are being made available to both Government and industry upon request.

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### Flight Clearance of STOVL Maneuver Technology Demonstrator Engine

A three-phase engine altitude development and flight clearance test program was conducted in the NASA Lewis Propulsion System Laboratory (PSL-3) in support of the Short Takeoff and Landing/Maneuver Technology Demonstrator (s/MTD) Program aircraft flight test. The s/MTD program's objective is to develop and demonstrate technologies for future fighter aircraft.

The primary test hardware consisted of a modified production F100-220 engine with a state-of-the-art multi-functional nozzle capable of pitch-axis thrust vectoring and variable-angle thrust reversing and a facility exhaust gas management system (EGMS) designed for unrestricted engine and nozzle operation in the axial, vectored, and reverse modes. Over 1000 measurements including pressure, temperature, strain, acoustic, and vibration were required. Data were recorded, reduced, and transmitted to the engine manufacturer (Pratt & Whitney Aircraft) in Florida within hours of acquisition by using a NASA Lewis-developed system that employed a MASSCOMP computer and the NASA Program Support Communications Network.

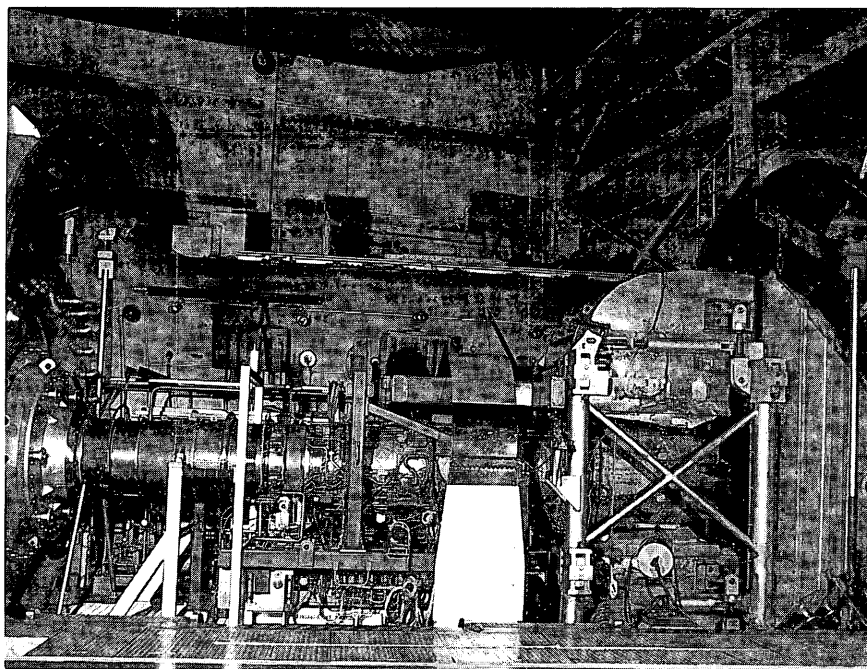
The first two phases of the program were conducted to demonstrate the operability, stability, and structural integrity of the engine and nozzle system. Engine power transient tests in the axial and vectored modes, nozzle vector transient tests, simultaneous engine power and nozzle vector transient tests, and zoom climb tests were conducted. The system was exposed to inlet pressures, inlet temperatures, and

altitudes ranging from 3 to 27.5 psia, 200 to  $-40^{\circ}\text{F}$ , and 2000 to 40,000 ft, respectively. After 125 hours of engine operating time, all test results showed that the system structural integrity, operability, and stability criteria had met or exceeded predictions in both the axial and vectored modes. As a result, the s/MTD aircraft was able to start its vector-only flight test program on schedule.

The final phase of the test program evaluated the reverser and its exhaust collection system. The nozzle reverser consists of two ports—upper and lower, each containing five variable vanes to control the exhaust flow direction. The reverser exhaust gas collection

system consists of two large ducts, each with aerodynamic contours designed to collect, turn, and transport the gases out to the main axial collector without the hot gases spilling into the test cell at the interface between each duct and the nozzle. The system was successfully tested over a range of flight conditions, reverse angles, and engine power settings from idle to maximum dry thrust. During all tests, test cell environmental conditions, altitude pressure, and cell temperature remained within acceptable levels.

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s/MTD system in PSL-3

# Icing

## New Icing Test Capability for Rotorcraft

NASA Lewis recently completed an icing test of a rotating OH-58 tail rotor in the Icing Research Tunnel. The rotor had a 13.3-cm chord and a 1.57-m diameter. The primary purpose of this test was to develop the techniques for operating a model rotor in an icing wind tunnel. The secondary purpose was to acquire data for use in developing various computer codes that predict ice accretion, ice shedding, and rotor performance degradation caused by ice on the rotors.

The test program addressed the following operational concerns: coordination of model and tunnel operation during startup, running, and shutdown; rotor reaction to ice accretion and shedding; safety and emergency procedures; and control of the model under these circumstances.

A substantial and unique data base on rotor ice accretion and performance was acquired in this test. Rotor blade ice shapes and corresponding iced-rotor torques were repeatable up to the onset of shedding for given icing conditions. When the ice shed, the inboard radial extent from which ice never shed was relatively repeatable, but shed times, locations, and quantities varied substantially from run to run. Although considered preliminary, these data will be useful for comparing the predictions of ice accretion codes, rotor performance codes, and ice shedding models.

The successful test of the OH-58 tail rotor prepared the way for a more sophisticated model rotor test run in the Icing Research Tunnel in late fiscal 1989.

A scale model of the UH-60 Blackhawk was tested with four NACA 0012 rotor blades, and data were acquired with a six-component force balance.

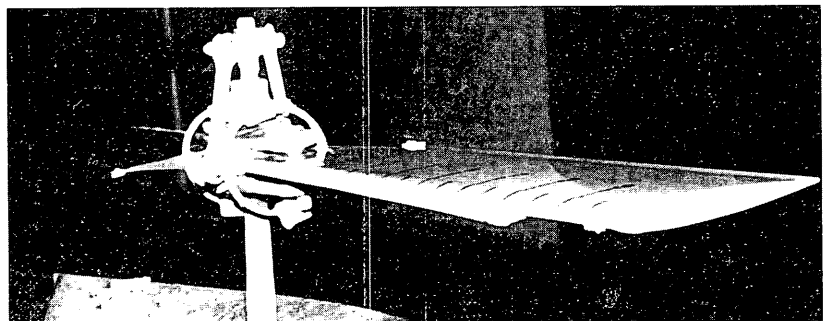
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*OH-58 tail rotor in Icing Research Tunnel*

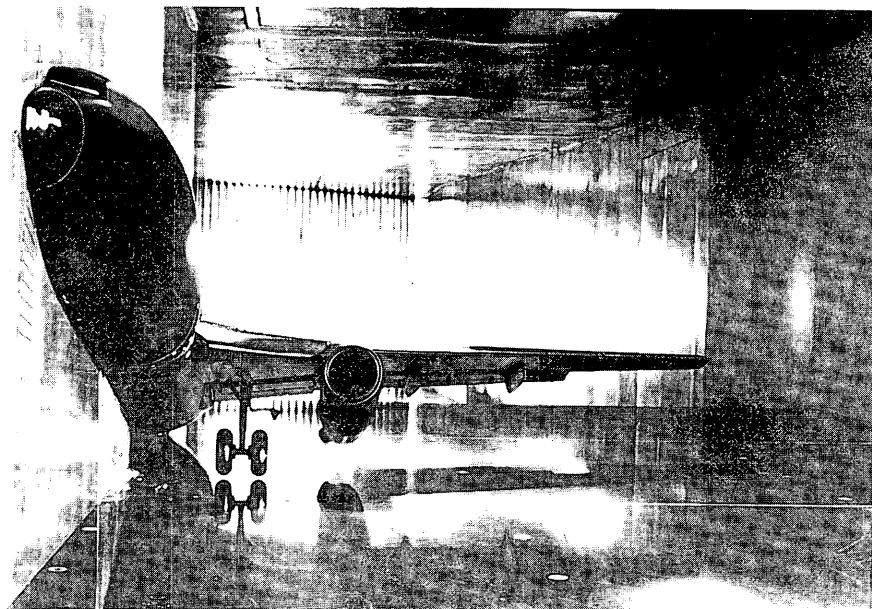


## Ground Deicing Fluids With Lower Aerodynamic Penalties

The Boeing Commercial Airplane Company and NASA conducted a joint test program in the NASA Lewis Icing Research Tunnel to evaluate the type I and type II ground deicing fluids used by the Association of European Airlines (AEA) during winter operations. Several experimental fluids were also tested as possible candidates to replace the then-current type II fluids. These fluids are employed during winter operations to prevent falling snow and freezing rain from freezing to the wings and causing potentially catastrophic losses in aerodynamic performance during takeoff. The type II fluids have been shown by the AEA to have far greater holdover times than the type I fluids. The object of the tests was to assess the aerodynamic performance penalties that result when an airplane takes off with ground deicing fluids on its wings.

AEA type I fluids are propylene glycol, which have holdover times similar to those of the ethylene glycol fluids commonly used in the United States for removing ice and snow from aircraft prior to takeoff. AEA type II fluids are non-Newtonian (thixotropic) fluids whose viscosity varies inversely with the shear applied to the fluid. A type II fluid is also called a thickened fluid because it has the viscosity of a gel when sitting on the wings of a grounded airplane. But during takeoff the air rushing over the wings exerts a shear stress on the fluid, thus reducing its viscosity and allowing the fluid to flow off the wing.

Tests were conducted on two models in the Icing Research Tunnel: a 0.091-scale three-dimensional half-



*Three-dimensional model of Boeing 737-200 ADV aircraft in Icing Research Tunnel*

model of the Boeing 737-200 ADV aircraft, and a 0.18-scale two-dimensional airfoil section at the 65-percent span of the 737-200 ADV aircraft. Wind tunnel test objectives were as follows: (1) correlate wind tunnel and flight test measurements of the aerodynamic effects of deicing fluids; (2) evaluate fluid effects at higher angles of attack than could be safely tested in flight; (3) expand flight test results for parametric variations of temperature, airfoil configuration, and fluid formulation; (4) contribute to the data base for establishing aerodynamic acceptance standards for ground deicing fluids; and (5) obtain data that contribute to a physical understanding of the lift loss mechanism. Current type I and type II fluids and eight new type II fluids were tested.

The data obtained from the wind tunnel tests included lift, drag, and pitching moment data through stall;

surface static pressures; initial film depth; fluid film depth during takeoff; video recordings of fluid flowoff; and boundary layer velocity profiles. A significant outcome was that the new type II fluids had lower aerodynamic penalties than the original type II fluids and did not degrade takeoff aerodynamic performance any more than did the type I fluids. As a result of this test program, the AEA airlines have already adopted the new type II fluids, one U.S. air carrier is using them, and some of the major U.S. airlines have begun testing these new type II fluids in preparation for use at selected airports next winter.

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# Facilities

## Mach Number Enhancement of 1- by 1-Foot Supersonic Wind Tunnel

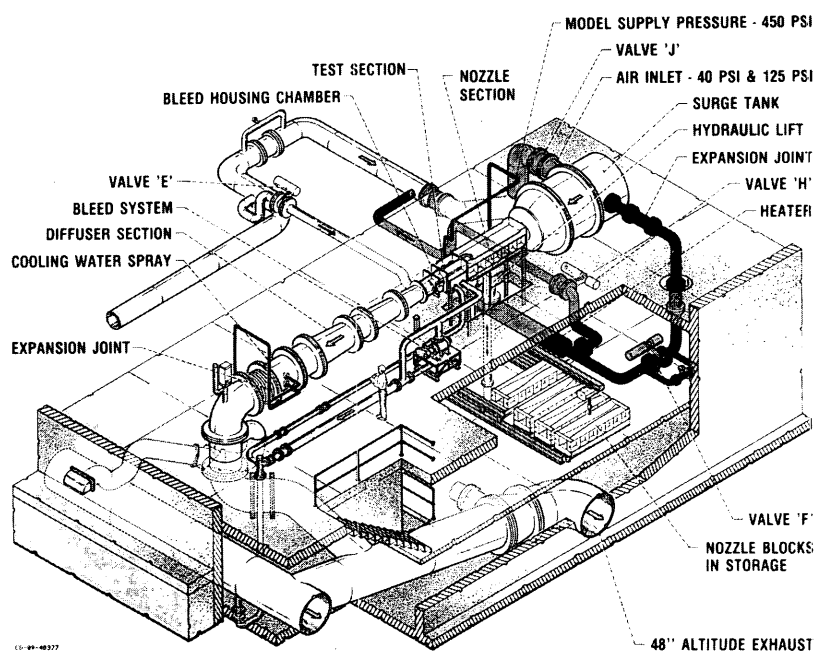
Because of renewed interest in the hypersonic flight regime caused by NASP-related programs, the 1- by 1-Foot Supersonic Wind Tunnel has been enhanced to provide continuous flow operation to Mach 6.

Mach 6 operation was provided by fabricating two new nozzles. The two-dimensional, fixed-geometry nozzles are contoured to operate at Mach 5.5 and Mach 6. In addition to the new nozzles, two other facility modifications were required to complete the enhancement. First, a new combustion air line was installed to provide inlet air pressures to 165 psia and mass flow rates to 80 lb/sec. Second, a 650-kW electrical resistance heater was added to the facility combustion air piping to boost air temperature and prevent liquefaction of the air at higher Mach numbers. The heater can provide controlled inlet air temperatures to 650 °F.

Additional pressure measurement capability was added to the facility. A 32-port, 5-psid pressure module and a 16-port, 500-psid pressure module were added to the pressure measurement system. The facility is now capable of recording 304 individual pressures. Also, the data system was improved to display real-time graphics during testing operations.

The tunnel now provides aerodynamic testing from the low supersonic ( $M_0 = 1.3$ ) to the hypersonic ( $M_0 = 6.0$ ) range in 0.5 Mach increments. The tunnel currently supports NASP testing, inlet development, code validation, and basic research.

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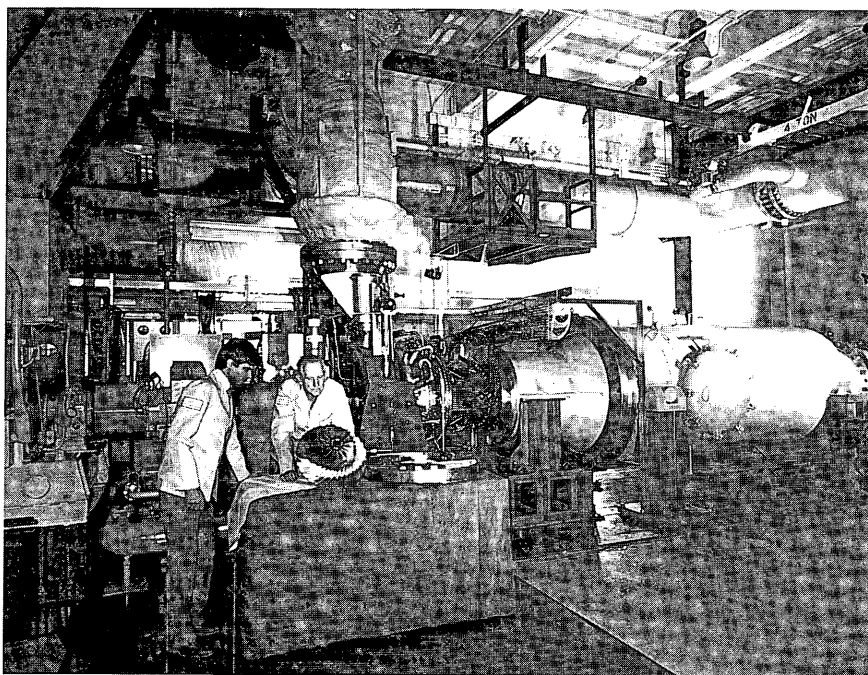
Variable-Mach-number 1- by 1-Foot Supersonic Wind Tunnel

## New Compressor Facility to Advance Small-Engine Technology

In order to improve component efficiencies in advanced small gas turbine engines, modern and versatile test facilities capable of providing high-quality test data are required. The Lewis Small Engine Components Compressor Test Facility meets this need with a number of unique capabilities.

Small engines are being used in an increasing variety of applications such as cruise missiles, tanks, helicopters, and auxiliary power generation systems. The efficiencies of small axial and centrifugal compressors are significantly below those of larger compressors. "Scaling" laws have been proposed to account for the degradation of performance resulting from thicker blades and shrouds, rougher relative surface finish, larger fillet radii, and variations in boundary layers and tip clearances. Small-engine technology can be developed further only through extensive testing of both large and small compressors under conditions that duplicate actual engine environments.

The facility provides the capability for investigating the performance of single-stage axial and centrifugal compressors and various stage combinations—achieving an overall pressure ratio of 30:1, a maximum speed of 60,000 rpm, and 6000 hp. The compressor can draw air from an atmospheric air intake, a 40-psig pressurized air source, or a refrigerated air source at  $-70^{\circ}\text{F}$ . The facility can handle airflow rates to 65 lb/sec, with the compressor exhaust discharged to the atmosphere or to an altitude exhaust. Compressors to 20 in. in diameter can be tested. Compressor performance is



*Small Engine Components Compressor Test Facility*

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monitored through an on-line data acquisition system with 608 pressure and 144 temperature channels. This test facility greatly enhances Lewis' turbomachinery test capability.

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## Design and Installation of Gear Noise Test Rig

In a helicopter the geared transmission is an efficient device for converting the high-speed, low-torque power output of the gas turbine engine to the low-speed, high-torque power required to drive the rotor blades. However, transmission gear noise (which has been measured at over 100-dB sound power) is the major source of noise in a helicopter cabin. This noise adversely affects health and disrupts communication. The Helicopter Transmission Noise Reduction Research Project was begun to solve this problem. Gear vibration and noise have been simulated by computer codes, but there is an acute need to validate these codes with experimental data taken under carefully controlled conditions. There is also a need for an experimental facility to help identify and develop advanced concepts for reducing helicopter transmission noise. The gear noise test rig was built to satisfy these needs.

The preliminary transmission design was analyzed in house by using existing gear dynamics computer programs. The test facility requirements were selected on the basis of the analysis. The facility and test transmission were designed under contract by Transmission Research, Inc., and the hardware was fabricated and assembled in house. A 200-hp, variable-speed motor powers the rig from one end, and an eddy-current dynamometer applies power-absorbing torque at the other end. The test gearbox is driven at speeds to 10,000 rpm. The dynamometer maximum speed is 6000 rpm. The maximum power that can be absorbed by the dynamometer is 175 hp. The gearbox can test spur

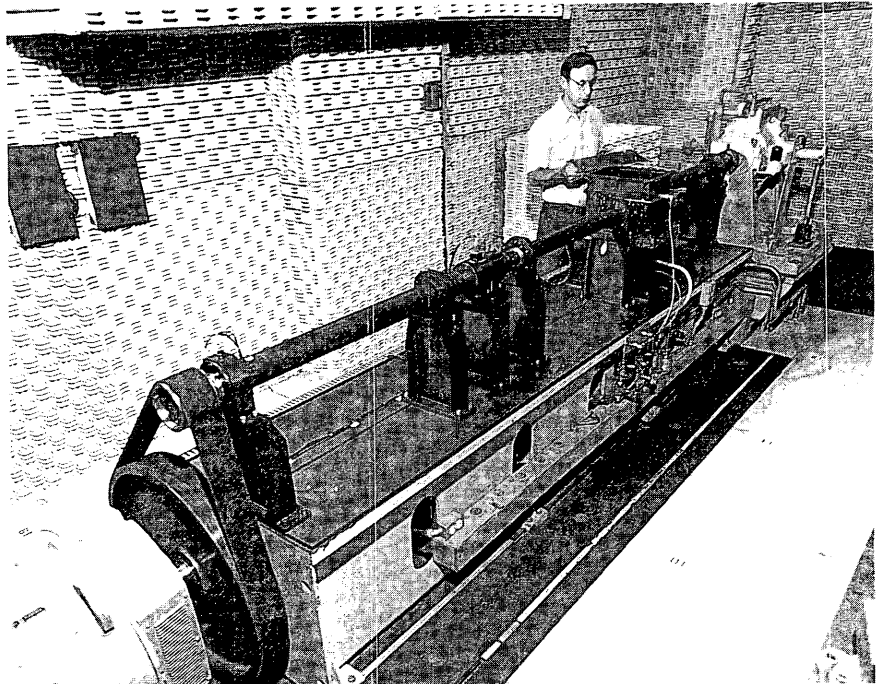
or helical gears of various ratios. The center distance between the input shaft and the output shaft is adjustable from 90 to 135 mm (3.5 to 5.25 in.). Space exists for optional flywheels on the input and output shafts to study the effect of input and output mechanical impedances on gearbox dynamics. Damping may be adjusted at the bearing mounts to study their effect on vibration propagation to the support structure. An alternative flexible mounting simulates the effect of a transmission mounted on a helicopter airframe structure.

The rig is instrumented to measure gearbox noise and dynamics. Measurement capabilities include

acoustic intensity, sound level, support structure forces, housing vibration, shaft lateral and torsional vibration, and gear tooth stress. Sound-absorbing material has been added to the test cell walls, ceiling, and floor to improve acoustic measurements.

This test facility makes it possible to experimentally study the parametric effects of new gear tooth forms and other advanced concepts on helicopter transmission noise. In addition, it will provide data to validate computer models for predicting gearbox dynamics, vibration, and noise for a range of design variables. The data and validated computer codes resulting

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*Gear noise test rig*

from the test program will provide a technology base for future quiet transmission designs.

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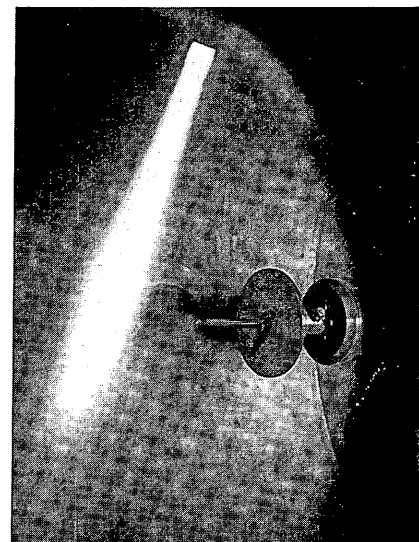
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### Low-Pressure Plasma Spray Facility

The current emphasis on high-temperature materials for aerospace applications has prompted increased awareness of the need for oxidation- and heat-resistant coatings. The development of these coatings requires a coating application process that is flexible, repeatable, and suitable for a wide variety of materials. Plasma spray deposition can provide high-quality metal, ceramic, or composite metal/ceramic protective coatings at a reasonable cost.

Plasma spraying is accomplished by feeding a powder of the desired coating material into an extremely high-temperature plasma. The plasma is created inside a plasma torch by passing an electric arc across a suitable gas or gas mixture, such as argon-helium. High velocities are achieved by allowing the gas, along with the entrained metal particles, to exit through a nozzle formed in one of the electrodes. The particles melt as they are rapidly propelled toward a substrate and, upon striking the substrate, they flatten and solidify to build up a coating.

Conventional ambient-pressure plasma spraying is carried out in an open-air environment. Although ambient-pressure spraying is adequate for a large number of applications, it cannot be used to produce dense metallic coatings: the presence of the atmosphere causes oxidation and limits flame velocity, which limits particle momentum. The result is a porous, oxidized coating that is inadequate for most high-temperature aerospace applications. In contrast, spraying into a soft vacuum (i.e., low-pressure



*Low-Pressure Plasma Spray Facility*

plasma spraying) allows high particle velocities and prevents oxidation, yielding dense coatings essentially free of oxides. These dense, oxide-free coatings can be engineered for oxidation or wear resistance, or they can serve as the bond coat layer under a thermally insulating ceramic in a thermal barrier coating. Also, free-standing shapes that may be impossible to fabricate by ambient-pressure plasma spraying can be fabricated by low-pressure plasma spraying.

The NASA Lewis Low-Pressure Plasma Spray Facility is one of few in the world that is both state of the art and devoted exclusively to research and development. Recent upgrades have produced a system with 120 kW of power, reverse-transfer-arc specimen cleaning, robotically controlled specimen and

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torch manipulation with a total of 5 degrees of freedom, and an independently pumped transfer chamber for efficient operation. Other process control and data acquisition capabilities are being installed in the facility to ensure process repeatability and real-time monitoring of processing. The facility is currently being used to fabricate bond coats for a thermal barrier coating program and composite monotapes for a metal matrix composite program.

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### **Modifications for Fan and Compressor Research Testing**

Modifications and additions to two areas that support planned research testing in the Engine Research Building were recently completed. The work included modifications to the variable-frequency power supply system and reestablishment of a refrigerated air system.

The modifications to the variable-frequency power supply system were required to improve the stability and accuracy of the drive motor control system's output frequency and to provide greater reliability and maintainability. Acquiring valid performance data for current and future aeropropulsion research programs requires a system capable of maintaining a given set speed over a long time at a wide range of throughflow and backpressures. The new equipment utilizes distributed processing and static drives to precisely control large rotating frequency converters. Smooth power at up to 5 MW is available for test rig drive applications.

The original refrigerated air system, which used ammonia, was removed a number of years ago for safety reasons. The reestablishment of the refrigerated air system was required to support future advanced compressor and fan research programs such as supersonic, hypersonic, and advanced small-engine technology and laser anemometry. The construction work included buildup modifications and installation of a large turboexpander, an intercooler, controls, and instrumentation. A new 30-in.-diameter piping system now connects the turboexpander system to the test cells.

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### Rehabilitation of High-Energy Fuels Laboratory

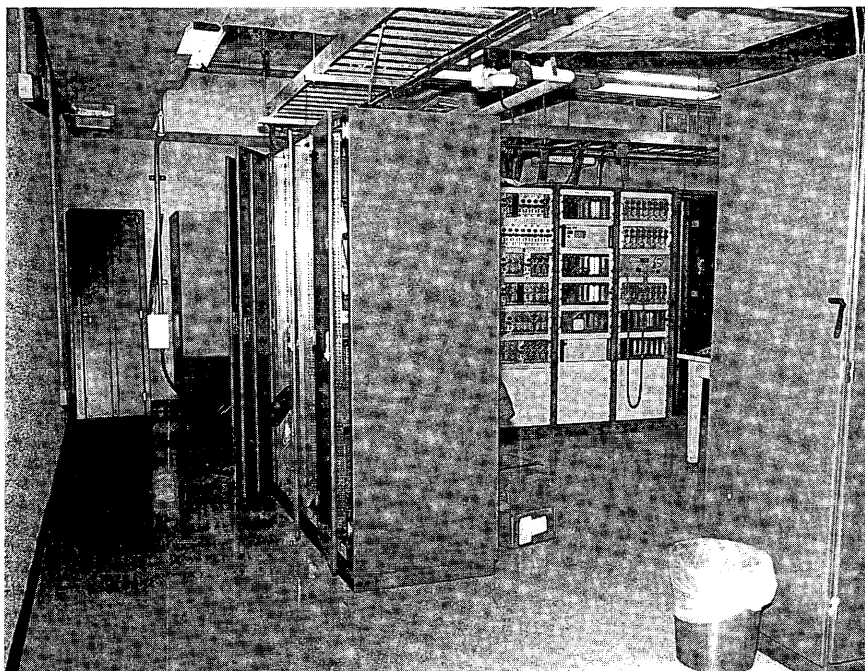
The High-Energy Fuels Laboratory has been rehabilitated so that research can be conducted on high-temperature structural composite materials for advanced propulsion systems.

Research, fabrication, and testing of ceramic and metal matrix composites will provide materials for new classes of propulsion systems in the 21st century. These materials, which are being developed for gas turbine engines, hypersonic aircraft, and space propulsion, require the fabrication and structural testing capability recently installed in this laboratory.

The rehabilitation project included construction of a 1440-ft<sup>2</sup> bay addition, replacement of the building exterior shell, a new hydraulic pump house, reglazing of exterior windows, replacement of air-conditioning units in the control room, and new exterior lighting.

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*High-Energy Fuels Laboratory*

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## Model Preparation Shop for 8- by 6-Foot Supersonic Wind Tunnel

Wind tunnel models are becoming increasingly more complex and are more heavily instrumented than in the past. This requires more assembly and checkout time. The models tested in the 8- by 6-Foot Supersonic Wind Tunnel are currently assembled at another location in the tunnel complex and then transported by truck to the tunnel test section, where final assembly and checkout are completed. This procedure is time consuming and limits the productivity of a tunnel that is in heavy demand.

A well-planned model preparation shop has been provided that has direct access into the tunnel. This shop allows wind tunnel personnel to assemble and check out a model prior to its installation in the test section. During assembly and checkout the tunnel may be used for other tests. A new entrance has been added for truck deliveries of models and equipment. Models are lifted from the trucks by an overhead crane and delivered to model preparation areas. A floor beam, cast into the floor of each model preparation area, allows models to be secured and stress tested. Once prepared, models are transported to the tunnel test section by wheeled carts over a floor that is at the same elevation as the tunnel loading area.

The work included the removal of an abandoned fuel building and construction of a new 2700-ft<sup>2</sup> one-story model preparation shop with direct access into the tunnel. The shop has six model preparation areas served by an overhead crane and is accessed by a 14-ft overhead door. Access to the tunnel is through an existing overhead door and an

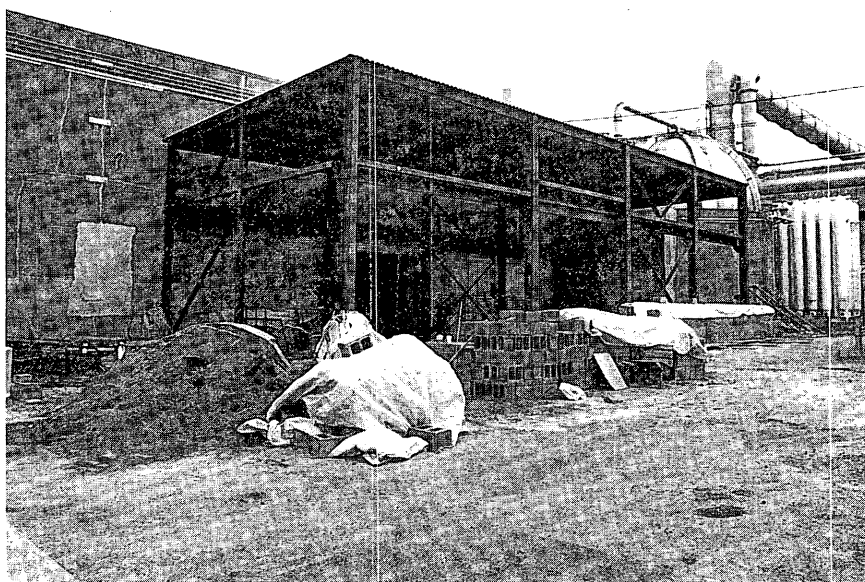
existing pressure door into the lower balance chamber. Construction work also included heating and air-conditioning, water, sewers, service air, electrical, and communications systems.

Performing certain assembly and checkout processes outside the tunnel test section greatly enhances the overall productivity of the tunnel because the test section is not tied up during nontest activities.

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*Model preparation shop*

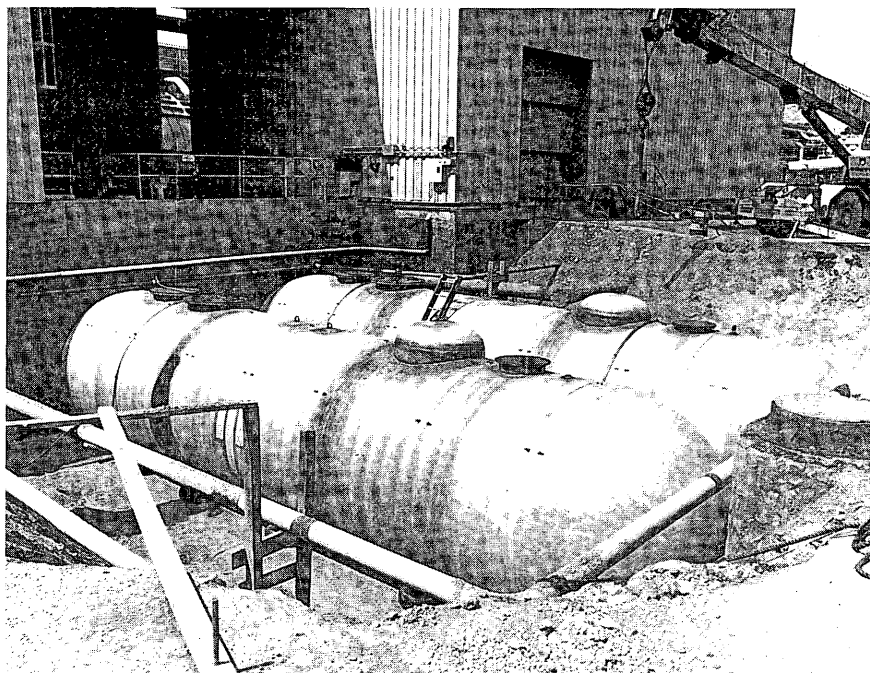


## Improvement of Propulsion Systems Laboratory

The NASA Lewis Propulsion Systems Laboratory (PSL) consists of four test chambers connected to the central air system and capable of testing large-scale airbreathing engine systems under controlled simulated altitude, temperature, and pressure conditions. System studies in the PSL evaluate engine thrust, fuel consumption, airflow, flow limits, blowout limits, temperature, pressure, flow distortion, acceleration, vibration, and starting characteristics. PSL 1 and 2, which went into operation in 1952, were placed in "indefinite shutdown" in 1979. PSL 3 and 4 were completed in 1972 and have undergone three major improvement projects in 1989.

The primary cooler, a critical component of the PSL facility, reduces the temperature of engine exhaust gases before final discharge through exhaust machinery. The cooler, which has been in operation since 1972, consists of two banks of 3- and 2-in.-diameter bare tubing and one bank of 2-in.-diameter finned tubing. The bare tubes had deteriorated because of extensive afterburning operation in the test cells. The bare tube banks in the primary cooler were repaired. The work included the removal of 1408 tubes (2816 tube joints) with a total weight of approximately 199,500 lb, fabrication and installation of new tubing, tube joint expansion, and tube bundle support plates, and hydrostatic testing after completion of assembly and testing.

Operation of the PSL facility at altitudes below 15,000 ft and Mach numbers below 0.4 has been limited by test cell bypass valve leakage and the possibility of test cell and



*New PSL fuel storage tanks*

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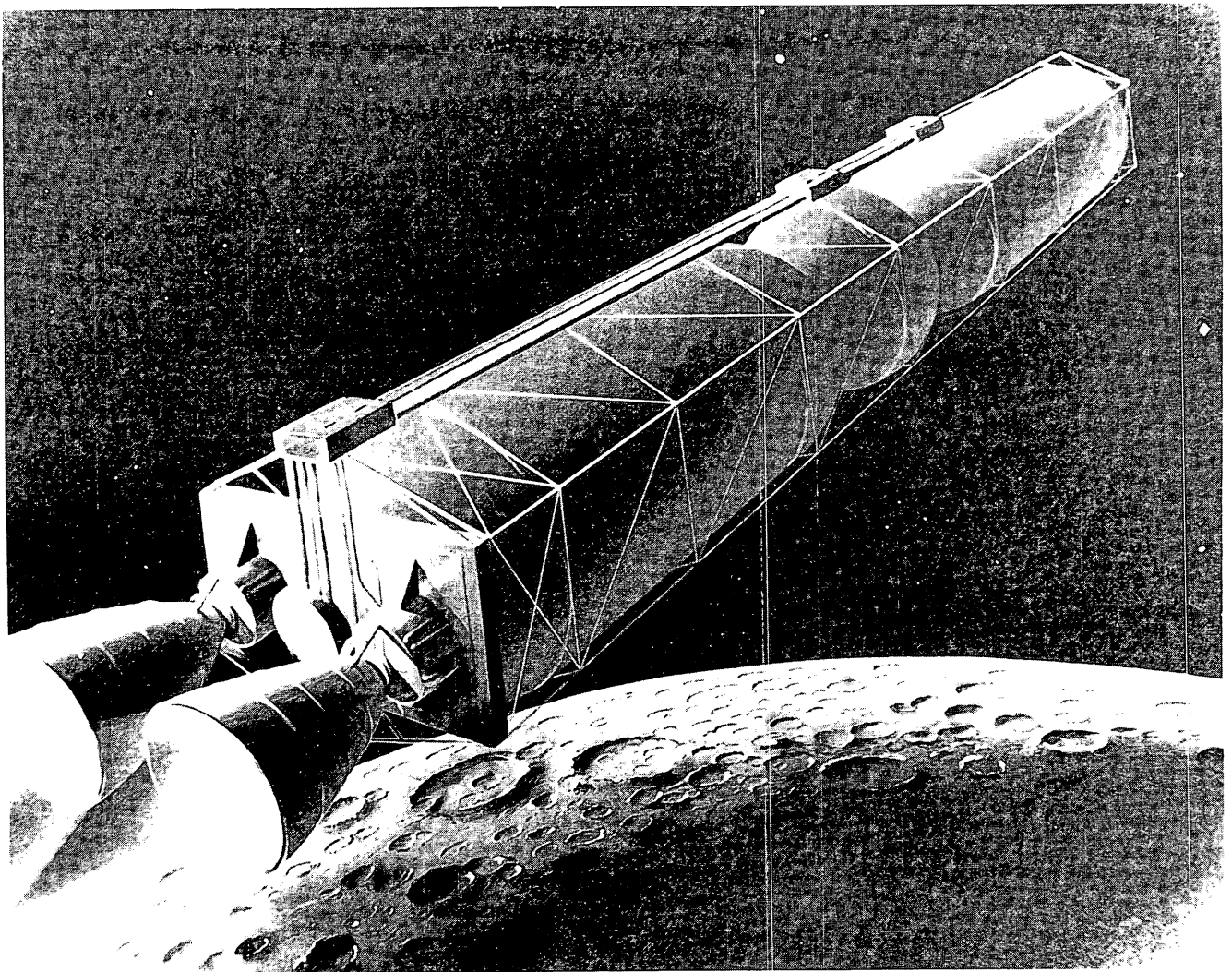
exhaust section overpressurization. In certain tests it is necessary to compare the altitude performance of research engines with their near-sea-level performance. Vent assemblies in each cell hatch now relieve pressure before it can build up to the design limits. Quick-opening personways allow rapid access to the test article, eliminating the time-consuming process of opening and closing the test cell hatch, thereby improving productivity.

Also, the facility's fuel supply storage system was modified. The existing above-ground fuel supply storage tanks and carbon steel piping that had corroded with age were removed. They had been a major source of fuel contamination for research engine testing. Three

"roadable" trailers (5000 gal each) used to store special fuels also were deactivated and removed. The work included the removal of carbon steel piping throughout the distribution system.

JP-4 and Jet A-1 are now stored in two 25,000-gal underground fiberglass tanks. All replacement piping, pumps, filters, and valving for the fuel distribution system are made of stainless steel and meet all current Environmental Protection Agency regulations.

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# Space Propulsion

## Strategic Objectives

- To remain in the forefront as a major NASA center for space propulsion research and technology required to meet current and future national needs for space.
- To capture development responsibility for the next-generation space hydrogen-oxygen engine needed for orbit transfer vehicles, upper stages, and Mars and lunar transfers and to vertically integrate our research and technology with system development activities.

# Programs

## Earth-to-Orbit Propulsion

The Civil Space Technology Initiative (CSTI) is a focused effort to develop the technology base for future space missions that will require efficient, reliable access to and operations in low Earth orbit. A key element of CSTI is the Earth-to-Orbit (ETO) Propulsion Program. Planned efforts are focused on enhancing engine performance, increasing component durability, more accurately predicting component and engine performance and service life, increasing quality and reliability through improved manufacturing processes, and developing engine condition monitoring, safety management, and controls for more cost-effective and reliable operation. Although focused primarily on fully reusable engines for manned vehicles, the resulting technology advancements and design and development tools will be applicable to expendable or partially reusable cargo delivery vehicles, as well as to growth versions and derivatives of the space shuttle itself.

The ETO Propulsion Program uses a phase approach in which fundamental analytical and design methodologies are initially developed in a technology acquisition phase. System level verification is then conducted in the validation phase through the use of large-scale subsystem testbeds. This phase approach is used in each of the three program elements: combustion devices, turbomachinery, and system monitoring and control. The products of CSTI will include ground and flight-qualifiable hardware, software, data, analysis and design tools, and processes and techniques applicable to mission-performing propulsion systems of the 1990's.

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## Launch Vehicle Project Office

The Launch Vehicle Project Office has expanded its operations during the year as the Nation and NASA moved forward in establishing a mixed fleet of expendable launch vehicles working in concert with the space shuttle. NASA Headquarters has directed Lewis to establish and manage launch services contracts for Government missions that can use intermediate-class vehicles (Atlas and Titan III) and to procure launch services from the U.S. Air Force for large-class vehicles (such as Titan IV) where commercial launch services are not available.

This year the Office has overseen the launch of the Fltsatcom F-8 communications satellite for the Department of Defense on Atlas vehicle AC-68R, the first launch services contract for NASA. In addition, a launch services contract to launch the Mars Observer spacecraft on a Titan III in 1992 was let with Martin Marietta Commercial Titan, Inc., and mission integration activities were begun with the Jet Propulsion Laboratory (JPL) and the NASA Marshall Space Flight Center, providers of the transfer orbit stage.

Mission-peculiar design was completed by General Dynamics Commercial Launch Services for the National Oceanic and Atmospheric Administration's geostationary operational environmental satellites and the NASA/Department of Defense

combined release and radiation effects spacecraft to be launched on Atlas I vehicles. Competitive procurement activities were also begun for intermediate-class launch services supporting the 1995 launch of the solar and heliospheric observatory being developed by the NASA Goddard Space Flight Center in conjunction with the European Space Agency.

Preliminary integration activities are under way for missions using Titan IV vehicles to be obtained from the U.S. Air Force. Two Titan IV's will be used for the JPL-developed Mariner Mark II comet rendezvous and asteroid flyby and Cassini to Saturn spacecraft. A Titan IV will be used to launch the Goddard-managed polar platform mission.

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## 1-kW Arcjet for Flight

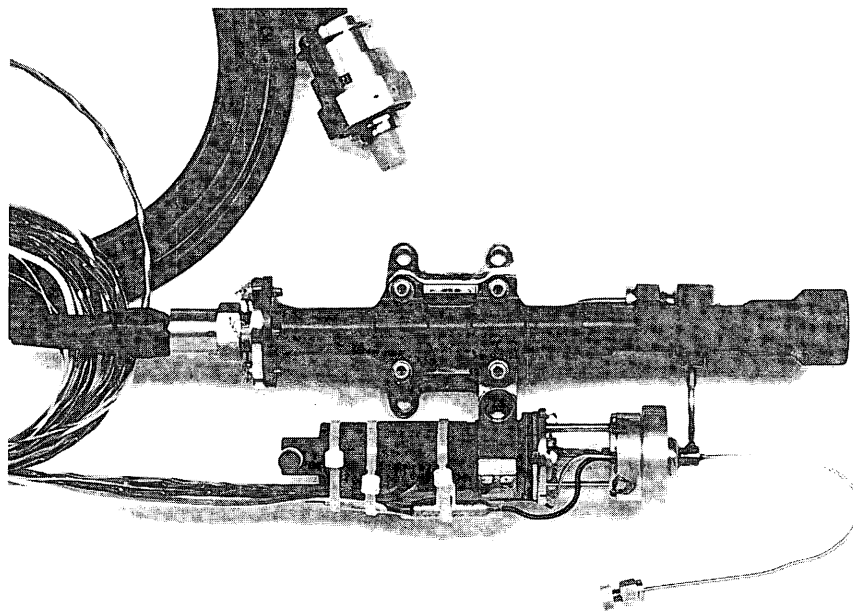
Arcjets extend the useful on-orbit life of geosynchronous communications satellites by about 50 percent. NASA Lewis therefore began a program to define and develop a 1-kW arcjet system to an operational level. Early efforts included an engineering-model-level hardware design, optimizations, and life verifications. In 1989 a flight type of arcjet system, including the arcjet and the associated power processor, was built and successfully integrated under a contracted effort. The arcjet design included geometric and surface treatment features that met stringent thermal interface requirements. The arcjet also successfully passed all environmental qualification and performance tests and is being prepared for qualification-level endurance tests. A flight type of power processor was built and successfully operated the developed arcjet over the full range of conditions expected in space. Additional tests verified that the 1-kW arcjet plume will not interfere with spacecraft communications.

On the basis of these results, a program to flight test the arcjet system was approved for fiscal 1990. Efforts are now under way to identify an appropriate space system on which to perform the space test, which should result in full acceptance of arcjets for operational applications.

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*Flight type of 1-kW arcjet*

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# Research & Technology

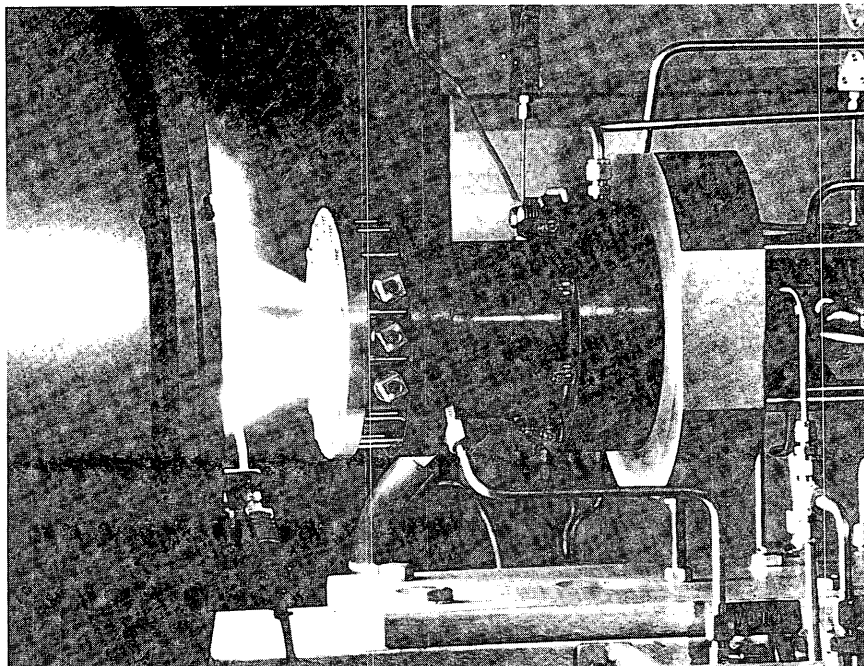
## Materials

### Thermal Barrier Coatings for Rocket Engines

A high-pressure fuel turbopump (HPFTP) supplies hydrogen to each of the three main engines aboard the space shuttle. These 72,000-hp pumps undergo extreme thermal transients as high as 18,000 deg C/sec during engine startup and shutdown. The attendant thermal shocks to HPFTP turbine blades are believed to contribute to crack initiation or propagation, resulting in blade removal and replacement far short of the desired design life. Insulating coatings, called thermal barrier coatings (TBC's), offer the potential to reduce the thermal transient experienced by the blade, thereby reducing blade damage and extending blade life.

The durability and insulating capability of TBC's were therefore evaluated in a high-heat-flux rocket engine environment similar to that in the HPFTP during engine startup. First, the heat flux to throat tubes in a hydrogen-oxygen rocket engine located at NASA Lewis was determined. Comparison with the predicted heat flux to the leading edge of HPFTP blades during engine startup showed that the Lewis rocket engine can simulate the heat flux to HPFTP blades. Second, the ability of TBC's to reduce metal temperatures during short thermal transients was examined by measuring metal temperatures in coated and uncoated tubes in the rocket engine. The significant temperature reductions for traditional TBC's indicate their potential to reduce the thermal shock to HPFTP blades during engine startup. Thermal models utilizing finite difference techniques were developed to predict the metal temperatures

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*Hydrogen-oxygen rocket engine testing*

beneath the thermal barrier coating of the coated tubes. Thermal models were also developed and used to predict the benefit of TBC's on the leading edge of HPFTP blades during the startup transient. Finally, TBC's applied by 12 vendors, the NASA Marshall Space Flight Center, and NASA Lewis were durability tested in the Lewis rocket engine. The extended cyclic lives of the three best coatings indicate the potential of TBC's to survive thermal cycling in the HPFTP environment.

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## Thermal Shock Resistance of Fiber-Reinforced Ceramics

Use of ceramic materials in the hot section of advanced reusable rocket engines promises improvements in performance, payload capability, and economics. Severe thermal transients during operation of the current space shuttle main engines push metallic components to the limit of their capabilities. Properly designed ceramic components have the potential to survive the hostile environment of an advanced rocket engine turbo-pump. Monolithic ceramics, however, lack toughness and can suffer brittle catastrophic failure. Continuous-fiber-reinforced ceramic matrix composites (FRCMC) are much tougher and thus should have greater resistance to thermal shock than monolithic ceramics.

A hydrogen-oxygen rocket engine capable of controlled thermal shock temperatures  $\Delta T$  from 1000 to 2500 deg C/sec was used to evaluate a number of monolithic and composite (FRCMC) specimens. Test results confirm the predicted improved thermal shock resistance of FRCMC.

At present the FRCMC technology is not mature enough for these materials to be incorporated into rocket engine designs. Additional research is required to identify and control the processing, fabrication, and design methodology for FRCMC rocket engine components.

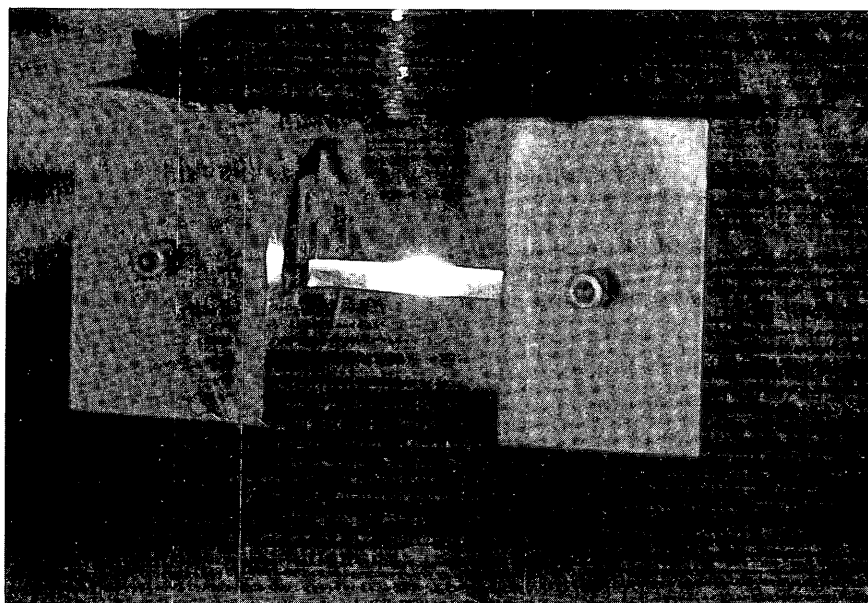
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*Turbopump thermal shock testing of ceramic matrix composites*



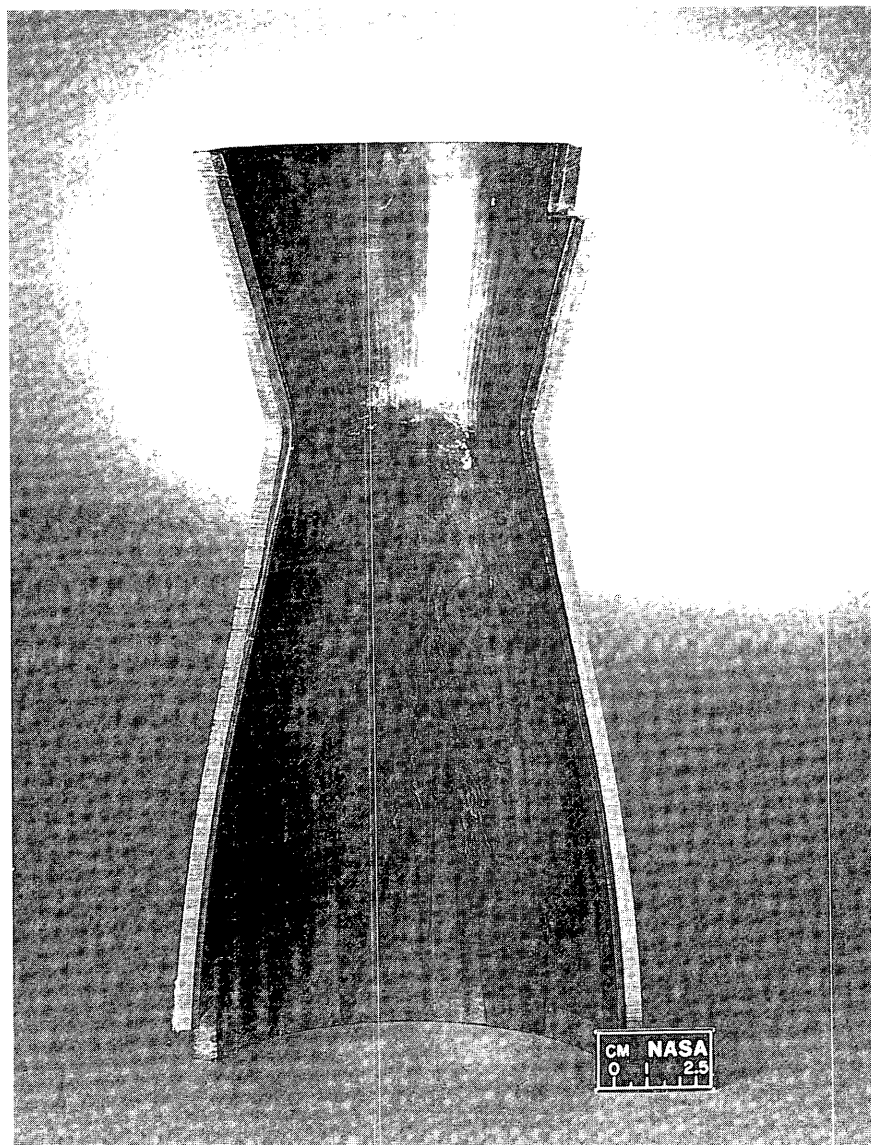
## New Materials for Rocket Nozzle Applications

Rocket nozzles represent an extreme environment for materials. One side of the rocket nozzle is exposed to the direct flame of the burning propellant while millimeters away the other side is immersed in a cryogenic liquid. Thermal fatigue and creep are encountered by the current materials used in rocket nozzles.

Any material used in a rocket nozzle must have high strength and high thermal conductivity at elevated temperatures. Good long-term stability of mechanical properties is also necessary. Although the currently used materials have good thermal conductivity at elevated temperatures, their strength and creep resistance rapidly degrade at temperatures above 500 °C. NASA Lewis is engaged in research to produce high-strength, high-conductivity materials to replace the current materials.

To achieve the high strength and conductivity desired, we are using precipitation strengthening to increase the strength of copper at elevated temperatures. By carefully selecting the second phase that is precipitated from the copper matrix, high strength can be achieved with only small decreases in thermal conductivity at elevated temperatures.

Two alloy systems are currently under development: Cu-Cr-Ag and Cu-Cr-Nb. Both are produced in the chill block melt-spinning facilities at NASA Lewis. The Cu-5Cr-2Ag alloy exhibits a strength of over 150 MPa (21.7 ksi) to 650 °C. Its thermal conductivity as determined from electrical resistivity measurements is comparable to that of pure copper at elevated temperatures.



*Experimental rocket nozzle*

Long-term stability is still being investigated. The Cu-Cr-Nb alloys have strengths of over 100 MPa (14.5 ksi) to 750 °C. Electrical conductivities at 500 °C are more than 90 percent that of pure copper. The long-term stability of mechanical

properties has been investigated through aging at 500 °C for up to 100 hours. Both materials are currently undergoing creep testing.

The preliminary results indicate that both materials have considerable



## Structural Mechanics

### Evaluation of Uncertainties on SSME Blade Structural Response

promise. Ongoing work will focus on production of larger quantities of materials and improved consolidation techniques to allow production of rocket nozzles and other structures.

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A probabilistic structural analysis of a space shuttle main engine turbo-pump blade has been under way at NASA Lewis for three years. The immediate objectives of this study are to evaluate the effects of uncertainties in geometry and material properties on the structural response of the turbopump blades. In this study uncertainties have been assumed to be normally distributed. The magnitudes of these uncertainties have been represented in terms of mean and variance. These two quantities were selected so that the absolute magnitude of uncertainty at any point was less than or equal to 10 percent of the original value.

A methodology has been developed that is based on probabilistic concepts and a statistical method of performing an experiment known as factorial design. It is considered economical and provides the significance and magnitude of the interaction effects for two or more variables. A parametric approach, on the other hand, is expensive and does not explicitly provide a direct estimate of the interaction effects.

The response of the blade, which is recorded in terms of displacement, natural frequencies, and maximum stress, has been evaluated and plotted in the form of probabilistic distributions. These distributions provide an estimate of the range of magnitude of the response and the probability of occurrence of a given response. An uncertainty up to 10 percent in the material properties had no significant effect on the response, but an uncertainty up to 10 percent in geometry, along the thickness, did significantly affect the structural response.

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## Capabilities of NESSUS Code

Probabilistic structural analysis assesses the effects of uncertain or random input parameters on structural response. Unlike the traditional deterministic analysis, in which geometry, material properties, and loading are assumed to be known, probabilistic structural analysis treats this input as samples from probability distributions. The approach makes it possible to assess the effects of fluctuating loads, variable material properties, and uncertain geometries on structural response. In the deterministic approach these uncertainties are not quantified and are accounted for by an empirical safety factor. Probabilistic structural analysis provides a more reliable and systematic way to evaluate structural performance and durability.

The NESSUS computer code, developed under the program Probabilistic Structural Analysis Methods for Select Space Propulsion System Components (PSAM), combines finite elements with probabilistic load and geometry input descriptions and structural reliability algorithms to provide an integrated approach to probabilistic structural analysis.

The current code consists of three major models: NESSUS/PRE, NESSUS/FEM, and NESSUS/FPI. NESSUS/PRE is a preprocessor that decomposes the spatially correlated random variables into a set of uncorrelated random variables by using a modal analysis method. NESSUS/FEM is a finite element module that provides structural sensitivities to all the random variables considered. A part of NESSUS, FPI (fast probability integrator), computes the sensitivity of the probability distribution for any response to the independent random variables. This information, quantified

by sensitivity factors, can be used to define the roles of the random variables in the reliability model.

Sensitivity factors indicate which random variables are most crucial and require the most accurate probabilistic description. Risk assessment analysis and computation of the safety index can be conducted once the probability density is known.

A sample probabilistic structural analysis has been performed on the space shuttle main engine blade. Random factors considered in the analysis include random centrifugal loads, random temperature, random pressure loads, and randomness in the material properties and geometry. NESSUS has been used to compute safety indices for the space shuttle main engine blade.

Risk assessment of the blade will be performed to determine whether a design is acceptable. For a rejected blade design, sensitivity factors will lead the designer to the most efficient way to improve the reliability of the blade design.

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## Nonlinear Structural Analysis of Rocket Nozzle Thrust Chambers

NASA Lewis has developed a capability for the nonlinear finite element analyses of structural components by using advanced viscoplastic models. The finite element solution technology developed for use with the MARC computer program employs simple and "smart" time-integration strategies. This leads to considerable savings in computational time for structural engineering problems, which generally involve complex geometries and loadings. The development of such solution technology was mandatory to make realistic viscoplastic models adaptable in component design.

The analysis of a regeneratively cooled rocket nozzle thrust chamber was undertaken to explore the benefits offered by realistic viscoplastic models and to demonstrate the suitability of the developed finite element solution technology for nonlinear structural analysis. Generalized

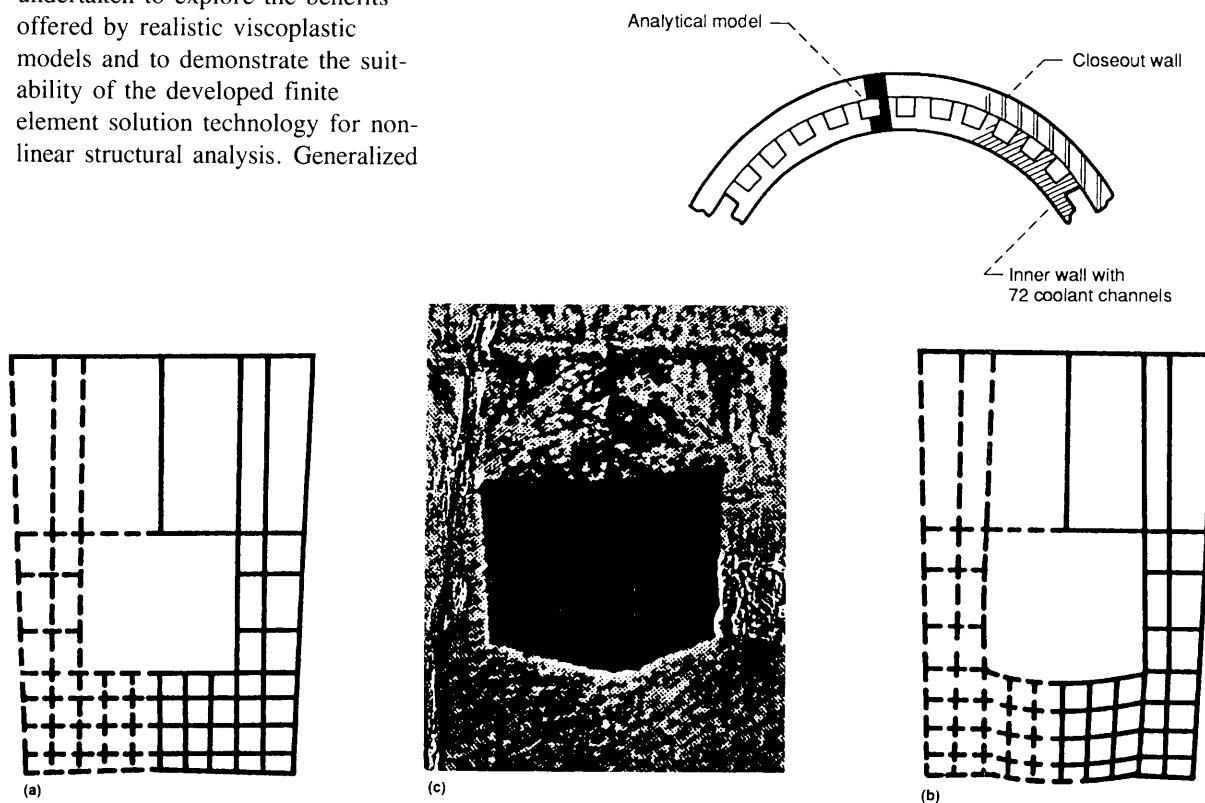
plane-strain isoparametric elements were used to model the smallest repeating segment of the cylinder wall. A viscoplastic model developed recently at Lewis by Dr. Alan Freed was employed to compute time-dependent inelastic strains.

The predicted deformed geometries of the component, after the first and sixth firing cycles, are plotted in the figure. A magnification factor of about 15 was applied to the deformed shape to facilitate visual interpretation of the results. The deformed "dog-house" shape of the cooling passage was observed in a cyclic experiment carried to 393 cycles. The analysis

utilizing the viscoplastic model and the finite element solution technology qualitatively predicted the progressively deformed shape of the cycled component.

This work is being extended to investigate the effects of employing tungsten-fiber-reinforced copper matrix composites for subcomponent geometries and to assess their service lives.

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Cooling passage geometries: (a) after one firing, (b) after six firings, (c) after 393 firings

## System Studies

### Advanced Space Analysis Office

The Advanced Space Analysis Office (ASAO), during the third year of its existence at NASA Lewis, has continued to define and expand its roles both within Lewis and within the Agency, with emphasis on advanced planning activities involving several NASA Headquarters offices. These activities comprise assessments and analyses of power, propulsion, and cryogenic fluid management systems and computation of launch vehicle trajectories. ASAO, working with the technology divisions, has continued to be a major contributor to the planning of bold new space initiatives. Members of the Exploration Study Team were recognized by the Awareness Committee for their significant contributions to planning and implementing both manned and robotic exploration.

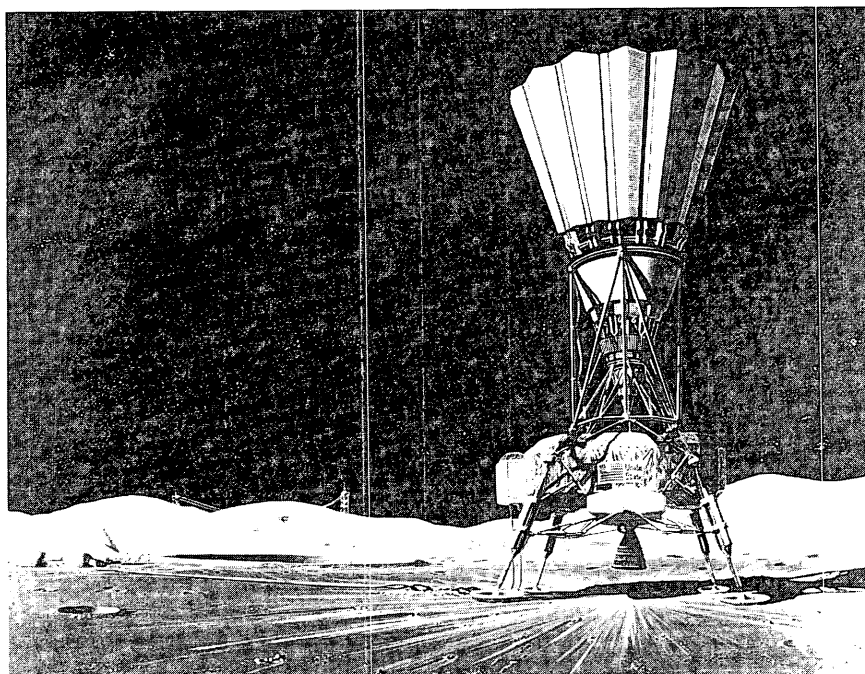
**Office of Exploration.**—Working under the Office of Exploration as a special assessment agent for power and propulsion, ASAO continues to conduct analyses and tradeoff studies that are helping to define the NASA missions of the next century. These studies include an examination of chemical and nuclear propulsion with and without aerobraking for travel to the planet Mars; assessments of nuclear and solar electric propulsion power systems; and studies on planetary surface exploration and habitation power systems, fluid system architectures for fuel storage and transfer in orbit, human-nuclear issues, and future propulsion technology concepts.

The ASAO has built an extensive capability to analyze low-thrust trajectories and the performance of vehicles that fly those trajectories. Many of the accepted computer codes for this type of analysis have

been acquired and are operating on Lewis computers, and ASAO personnel have gained substantial experience in the operation of those codes. The result is that Lewis has one of the leading capabilities in the Nation for analyzing low-thrust missions. This capability has been used to study nuclear and solar electric vehicles for exploration missions to Mars and its moons, orbit raising of communications satellites, and the performance of a nuclear fusion rocket for transfer from Earth to Saturn and return to Earth. ASAO will continue to use its low-thrust trajectory analysis capability for the study of lunar and Mars exploration missions for the Office

of Exploration and will also continue to modify and refine the analysis tools.

**Office of Space Flight.**—In the past year ASAO was also involved in a number of expendable launch vehicle (ELV) activities for the Office of Space Flight, including supporting preliminary and critical design reviews for the four currently active ELV missions (Fltsatcom, GOES, CRRES, and Mars Observer). Completing the radioisotope thermoelectric generator data book for performing risk assessments, managing a study to investigate the need for a new intermediate class of launch vehicle, and keeping current the ELV data base and simu-



SP-100 thermoelectric lunar lander (100 kW)

lations by using updates from vehicle manufacturers. Additionally, an upgraded Centaur study, a follow-on to the Centaur/Shuttle C upper stage feasibility study performed for OSF and reported last year, is being performed to determine the technical feasibility and mission performance requirements resulting from modifying the Centaur into an upper stage for heavy-lift vehicle (HLV) applications. This study will define how an upgraded Centaur could complement the role of the space transfer vehicle and enhance mission performance on such HLV concepts as NASA's Shuttle C, the Department of Defense's advanced launch system, and growth versions of the largest current ELV, the Titan IV. Finally, ASAO is developing the capability to compute trajectories for the Shuttle C/Centaur launch vehicle configuration.

**Office of Space Station.**—ASAO is participating in a NASA-wide effort to define Space Station *Freedom* evolutionary reference configurations. The Evolutionary Working Group is seeking to define evolutionary design requirements and to identify those advanced technology developments necessary for the space station to support a broad range of manned and unmanned exploration missions throughout the solar system. Study efforts have focused on on-orbit fluid management concepts associated with the accommodation of R&D fluids and propellants by the evolutionary space station infrastructure, nuclear accommodations and issues associated with nuclear vehicles and power systems at the station, and growth concepts for the power system.

**Office of Aeronautics and Space Technology.**—Studies are ongoing in

evolutionary space infrastructure power and propulsion requirements based on projected future activities of humans in space. Advanced technologies are being identified that enable a wide variety of possible missions with minimum development resources and adequate lead times. A computer model is also being developed to allow user-interactive manipulation of mission scenario timelines, associated technology requirements, and projected technology readiness dates in order to plan and develop future exploration missions and to assess impacts of assumed mission scenarios on technology development programs.

**Office of Space Science and Applications.**—Lewis is participating in a Mars Rover Sample Return (MRSR) mission study being conducted under the sponsorship of the Office of Space Science and Applications. This year ASAO coordinated the involvement of several Lewis organizations in the areas of ascent/descent propulsion, communications, structures (frictionless drives), and launch vehicles and characterized power system options for surface rover applications. Those power systems included dynamic isotope power systems and solar photovoltaics with energy storage. ASAO also supported the MRSR management team by providing launch vehicle options and performance parameters for the MRSR mission.

In order to facilitate its many study activities in the areas of power, propulsion, and cryogenic fluid systems, ASAO is letting three task order contracts, one in each area. Tasks will continue to be worked by NASA in-house teams supplemented by the task order contractors.

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## Health Management Systems for Rocket Engines

Between-firing inspections and analyses of reusable rocket engines are manpower intensive and difficult and are therefore expensive. In order to improve operational and testing effectiveness, an automated diagnostic system is being developed for rocket engine health management.

The conceptual design of the system has been completed. It combines elements of expert systems and advanced pattern recognition techniques such as neural networks. The expert system element will follow rules established by engineers and technicians familiar with inspection and data analysis to arrive at a diagnosis of the rocket engine health. The expert system is able to automatically consult a number of data bases. Assembly histories, sensor value trending predictions, and complex engine models are supplemented by pattern matching and hypothesis testing. This is done via neural networks that mimic human capabilities to compare and recognize patterns, as well as react to unexpected events. These techniques will initially utilize test stand data from the space shuttle main engines (SSME) to develop a diagnostic and prognostic monitoring system. However, the long-range goal of the system includes in-flight capabilities for all types of space transportation engines.

NASA Lewis is currently conducting research to support development of this system for rocket engines. Rocketdyne has developed a prototype expert-system-based health monitoring system for the high-pressure oxidizer turbopump of the SSME. This system defines a knowledge base that accommodates

instrumentation data, hardware inspection data, and life analysis techniques. A joint effort between NASA Johnson Space Flight Center, Netrologic, Inc., and NASA Lewis is applying neural networks to SSME ground test data. Extension to in-flight monitoring for fault detection is also being planned. Another contract to provide the fault detection status of the SSME test stand firings uses a pattern recognition algorithm developed by United Technologies Research Center. The results from the application of this algorithm will be used to formulate an information-processing methodology for life management and health monitoring.

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and OSF

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## Propulsion Components

### Integrated Hydrogen-Oxygen Auxiliary Propulsion

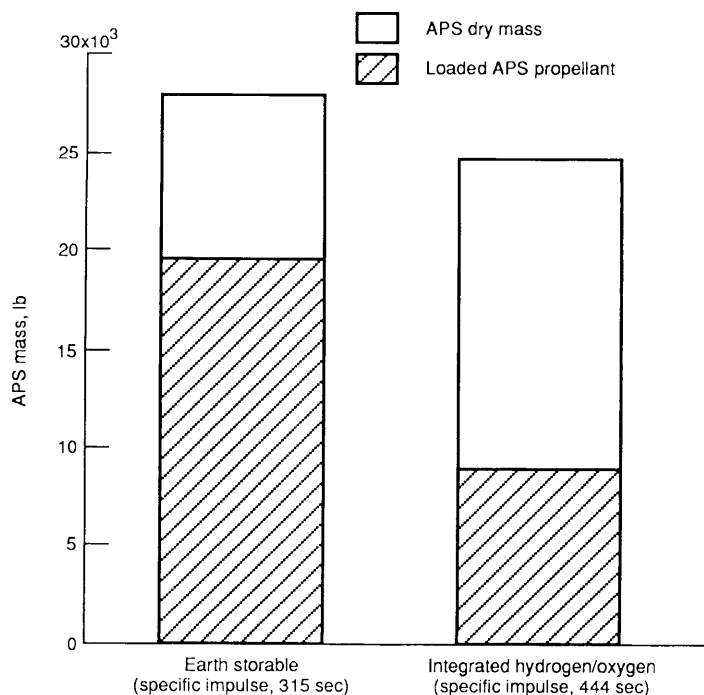
The auxiliary propulsion systems (APS's) of Earth-to-orbit vehicles presently represent a significant fraction of the mass delivered to orbit. For example, the shuttle orbiter's APS's, which use Earth-storable bipropellants, represent up to 18 percent of the shuttle's on-orbit mass. Technologies that increase the performance of APS's offer significant increases in vehicle payloads.

In-house studies were begun to compare the use of an integrated, cryogenic hydrogen-oxygen APS concept and state-of-the-art Earth-storable APS's for future Earth-to-orbit vehicles. Integrated hydrogen-oxygen systems would scavenge propellants from the launch propulsion system and deliver them to APS thrusters operating over a wide range of propellant states. The combination of more energetic propellants and propellant scavenging would significantly reduce APS propellant mass. The elimination of toxic and corrosive Earth-storable propellants may also offer major benefits for ground operations. The payload benefits for integrated hydrogen-oxygen systems were found to be mission dependent. For a Space Station *Freedom* rendezvous mission ( $\Delta V$ , 1000 ft/sec), a mass savings of 3200 lbm was projected for the integrated hydrogen-oxygen APS over the current state of art. On the basis of these results a contracted program was begun to analyze the effects of integrated hydrogen-oxygen auxiliary propulsion on mission performance and operations. The effort will involve the participation of several other NASA centers to ensure that all relevant issues are addressed.

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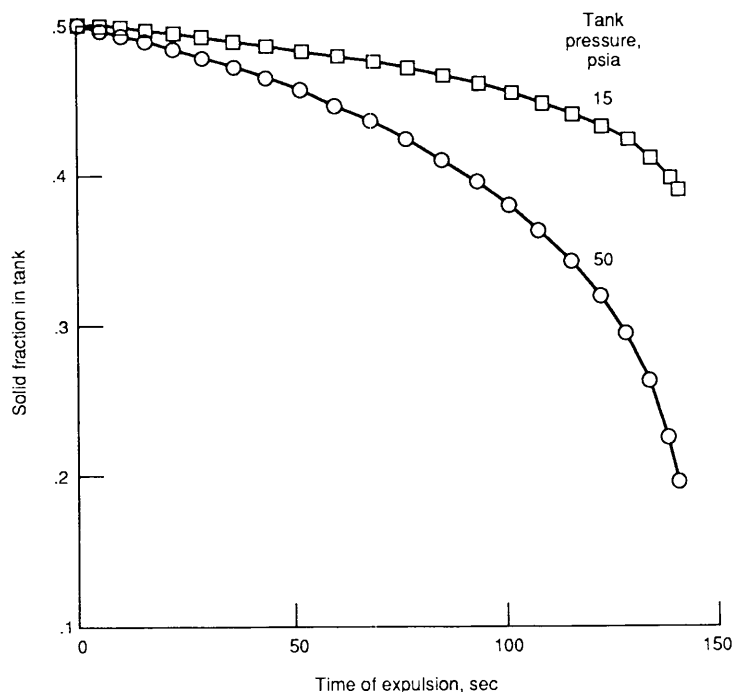
*Mass saving projected for integrated hydrogen-oxygen auxiliary propulsion system*

## Analytical Studies of Slush Hydrogen

Solid-liquid mixtures of hydrogen, known as slush hydrogen, are being considered for use in fueling the national aerospace plane (NASP). Slush hydrogen offers the advantages of increased density and heat capacity relative to normal-boiling-point liquid hydrogen. Higher densities offer reductions in NASP vehicle weight; increased heat capacity provides additional aircraft cooling capability. Although some experimental work was performed in the past, many technical issues related to storage and transfer of slush hydrogen remain unresolved. No information exists on the melting of solid hydrogen during pressurized expulsion from a storage tank, and no predictions are available on losses during pipe transfer. NASA Lewis has developed analytical codes to address these issues.

The first code, call FLUSH, calculates pressure drop and solid fraction for slush hydrogen flowing through a pipe system. The computer program solves the one-dimensional energy equation to obtain loss estimates. The estimates of pressure drop and solid fraction loss can be useful in determining parameters important to the design of transfer lines. FLUSH has been used to estimate the solid hydrogen loss in pipelines at K-Site, NASA Lewis' slush-hydrogen test facility located at Plum Brook Station, Sandusky, Ohio. A NASP special publication provides details of the FLUSH computer program.

A second code, called EXPL, predicts tank thermodynamics during the pressurized expulsion of slush hydrogen. EXPL was modified from an earlier version of the code that predicted tank conditions for liquid-



Comparison of calculated slush-hydrogen solid fraction at inlet gas temperature of 540 °R

hydrogen expulsion. EXPL solves the one-dimensional energy equation to calculate tank wall and ullage gas temperatures, pressurant gas requirements, and solid fraction change during the expulsion process. Output from the EXPL code plots slush-hydrogen solid fraction loss against expulsion time, for example, for tank pressures of 15 and 50 psia using gaseous-hydrogen pressurant at 540 °R. The large difference in the final solid fraction for the 15-psia and 50-psia cases is due to the larger inlet gas requirements with the 50-psia case; more pressurant gas implies an increase in energy transferred to the slush hydrogen. EXPL has also been used to predict tank conditions for tests to be performed at K-Site, as documented in a separate NASP publication.

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### Oxygen Turbopump With Gaseous-Oxygen Turbine for Dual Expander Cycle

A liquid-oxygen turbopump with a gaseous-oxygen turbine drive, subcritical rotor design, and liquid-oxygen-lubricated hydrostatic bearings was designed, fabricated, and tested by Aerojet Techsystems for the Orbit Transfer Vehicle Rocket Engine Technology Program managed by NASA Lewis. The purpose of the program is to develop the propulsion technology necessary to move space vehicles from low Earth orbit to geosynchronous orbit or other high Earth orbits. The orbital transfer vehicle's propulsion system requirements and goals of tank head starts, throttleability, high specific impulse, high reliability, human rating, and long life are of particular importance to the liquid-oxygen turbopump.

In order to attain the highest chamber pressure and the highest specific impulse for a given engine operating envelope, a dual-expander-cycle engine was designed. In the dual expander cycle, gaseous hydrogen drives the fuel pump and gaseous oxygen drives the oxidizer pump, eliminating the need for interpropellant seals and purges. However, material compatibility and operation of a turbine in 860 °R gaseous oxygen are critical technology issues for the liquid-oxygen turbopump and the dual-expander-cycle engine. Other issues addressed by this turbopump design include liquid-oxygen-lubricated hydrostatic bearings, throttleability, thermal expansion and contraction characteristics, and performance.

Designed for a 3750-lb-thrust, dual-expander-cycle rocket engine, this turbopump features a 156-hp, single-stage, full-admission impulse turbine;

an axial-flow inducer; a two-stage centrifugal pump with unshrouded impeller; long-life, liquid-oxygen-lubricated, self-aligning, hydrostatic bearings; and a subcritical rotor design. It is constructed of Monel, a nickel-copper alloy, which has low ignition potential in oxygen. The pump was designed to deliver 34.7 gal/min of liquid oxygen at a discharge pressure of 4655 psia and a shaft speed of 75,000 rpm.

Testing has demonstrated subcritical rotor operation, successful operation of a turbine in ambient-temperature gaseous oxygen, unassisted hydrostatic bearing starts, and stable and predictable pump performance over an operating range of 40 to 120 percent (ratio of design flow to speed).

Material loss in the bearings was minimal. The maximum test speed attained (~69,800 rpm) was limited by the available turbine supply

pressure. Although life testing and testing with warm (860 °R) gaseous oxygen in the turbine must still be conducted, results of testing to date indicate that a gaseous-oxygen-driven liquid-oxygen turbopump is feasible.

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Buckman, P.S.; Hayden, W.R.; and Sabiers, R.L.: Orbital Transfer Vehicle Engine Turbopump Oxygen Series A and B Test Report. NASA Contract NAS3-23772-B, Apr. 1988.

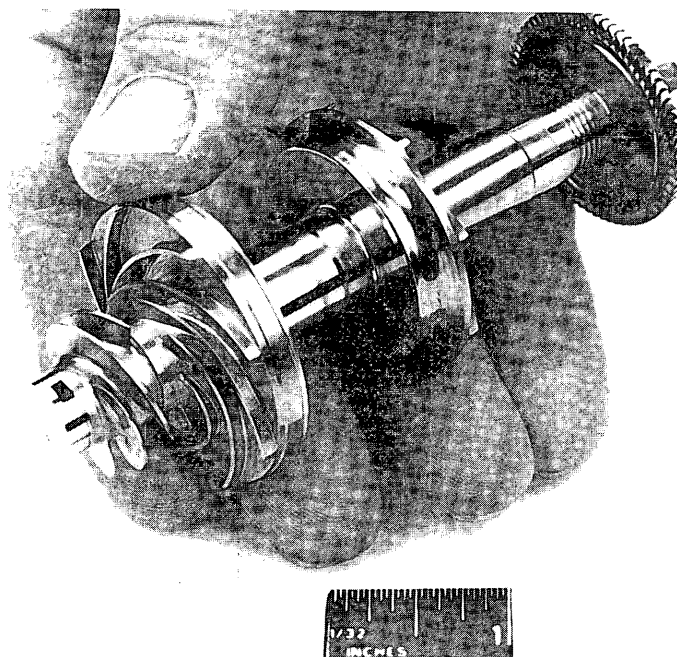
Buckman, P.S.; Shimp, N.R.; Viteri, F.; and Proctor, M.: Design and Test of an Oxygen Turbopump for a Dual Expander Cycle Rocket Engine, AIAA Paper 89-2305, July 1989.

Schoenman, L.: Oxygen TPA Material Ignition Study. Aerojet TechSystems Company Report 23772-M-42, Nov. 1986.

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*Liquid-oxygen turbopump*

## Flight Test of Arcjet Auxiliary Propulsion System

The 1.4-kW-class arcjet thruster is a logical evolution of the successful electrothermal hydrazine thrusters (resistojets) being used on spacecraft for geosynchronous stationkeeping. A NASA Lewis in-house research and technology program begun in 1983 led to NASA and industry efforts to develop this breakthrough technology in 1984. Since that time many design modifications have resulted in mature flight-quality hardware. Life testing was performed with hydrazine composition gases for a period of time exceeding twice the actual mission requirements. A life test using high-grade hydrazine as the propellant is now starting in order to characterize any changes from previous system performance.

It is now desirable to have the hydrazine arcjet systems integrated onto a host free-flying spacecraft by a spacecraft contractor. The spacecraft will be placed on orbit and the arcjet systems used for stationkeeping. If a geosynchronous mission is unavailable, the stationkeeping function will be simulated on a low-Earth-orbiting spacecraft. Arcjet system specific impulse is 450 sec and the thrust level is 45 millipounds.

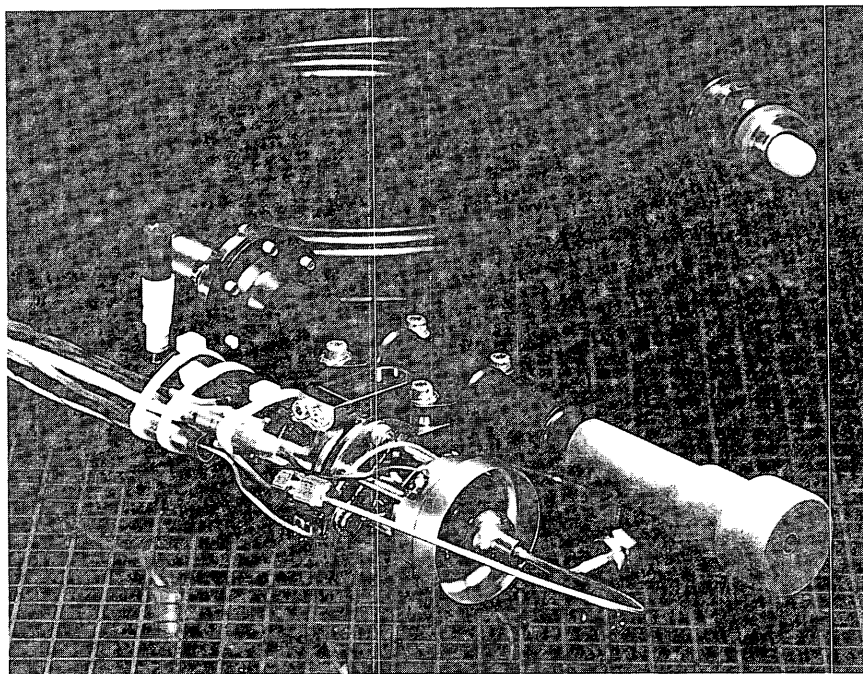
The overall objectives of the arcjet flight test are to assess hydrazine arcjet operation in a space environment and to evaluate arcjet compatibility effects on spacecraft operations. This flight test is necessary to characterize any electromagnetic interference that may result from spacecraft interaction with functioning arcjet systems. The flight demonstration will also verify thruster performance and thermal compatibility with the spacecraft in a space environment. A successful

demonstration of this technology will foster the acceptance of electric propulsion by the spacecraft industry and result in a commercial source for the production of arcjet systems.

Selection of a contractor/spacecraft and award of the flight contract is anticipated for the second quarter of fiscal 1990. Data on arcjet system operation will be supplied to Lewis by the contractor. Data will continue to be supplied until the end of either the arcjet lifetime or the spacecraft fuel supply.

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*Arcjet auxiliary propulsion system*

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## Combustion

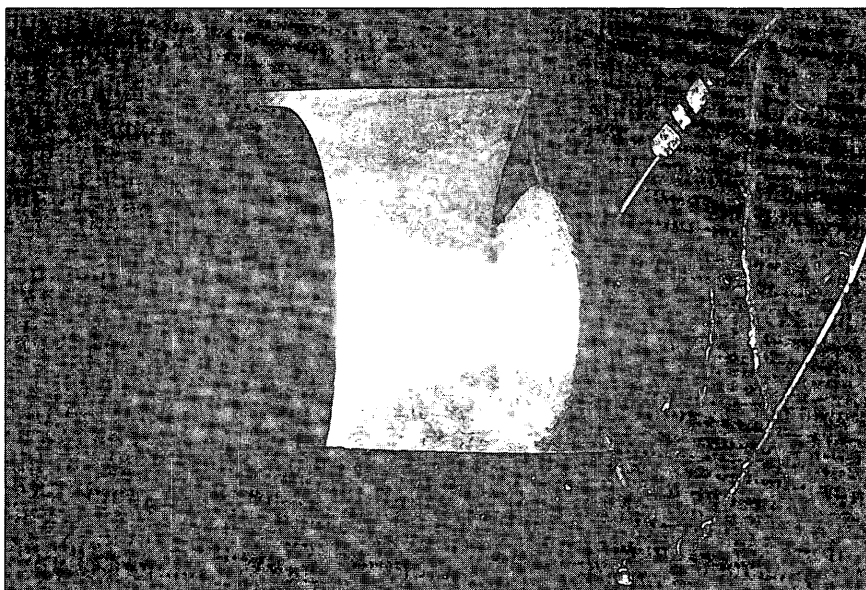
### Ignition and Combustion of Metallized Propellants

As space activity and space exploration continue to expand, the demand for more-efficient launch, orbit transfer, and interplanetary vehicles will continue to increase. Both NASA Lewis and industry have been investigating metallized propellants, which consist of a powdered metal suspended in a conventional liquid fuel. Theoretically, specific impulse, bulk propellant density, or both are increased by using a metallized fuel, resulting in more total payload delivered.

An experimental program was conducted at NASA Lewis to investigate the ignition and combustion properties of an aluminum/JP-10 gel fuel burned with oxygen by using liquid rocket engine technology. The metal loading of the fuel was 60 wt % aluminum. Typical chamber pressure was 100 psia and typical thrust was approximately 50 lbf. Total engine efficiency was measured and compared with the efficiency for neat liquid kerosene (RP-1) burned with oxygen. The mixture ratio was varied to cover fuel-rich and oxidizer-rich conditions. Chamber length was varied from 8 to 22 in.

The metallized propellant was tested in the same hardware as the RP-1 and exhibited similar performance results. The aluminum/JP-10 gel was approximately 2 to 6 percent less efficient than RP-1. Mission analysis has shown that even with a lower efficiency the aluminum/JP-10 gel will still have a larger payload capability than the neat RP-1 fuel.

Neither the non-Newtonian properties of the fuel nor the presence of the solid aluminum caused any significant operational problems with the experi-



*Metallized-propellant engine during testing*

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mental program. The fuel injector orifices remained clear during a run, wall deposits were minimal, and multiple firings were easily accomplished. These subscale experiments are a promising beginning toward the design of future launch vehicle and upper stage propulsion systems.

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## Multicompartment Ignition

Heavy-lift launch vehicle studies have shown potential mission and payload benefits from using liquid-oxygen and hydrocarbon fuels as propellants. These large, high-pressure engines will utilize a multicompartment combustion chamber. For simultaneous and smooth ignition an ignition source is needed in each compartment. The ignition source must be reliable and reusable and have a short ignition delay and a simple design for easy installation and maintainability.

After an ignition system evaluation, three ignition concepts were selected for the experimental evaluation: spark torch, laser-induced spark, and catalytic ignition. The hydrocarbon fuels used in the program have been gaseous methane ( $\text{CH}_4$ ) and liquid kerosene (RP-1). Several spark torch igniters have been evaluated; they ignited the methane and RP-1 over a wide range of mixture ratios and igniter chamber pressures. The reliability was nearly 100 percent.

The laser-induced spark igniter is presently being evaluated in a sub-scale gaseous oxygen/RP-1 chamber with a near-infrared laser as the ignition source. High-power, optical-fiber laser transmission is also being tested. Calibration of the laser and the optics is nearly completed. Sparks have been reliably produced in ambient conditions and a butane-air mixture ignited. The results of the initial testing verified the predicted large power loss for optical-fiber laser transmission.

A catalytic igniter has been tested with a platinum catalyst. However, because of insufficient residence time provided for the catalytic process, ignition was not attained for the



*Laser-induced spark generation*

gaseous oxygen-methane mixture. In future experimental efforts, variables such as catalyst type, catalysis staging, oxidizer and fuel preconditioning, and igniter geometry will be studied so that an effective design can be produced.

A university grant has been awarded to the Center for Space Propulsion Engineering at Penn State University to carry out a concurrent laser spark ignition research program. This research program will study the effect of incomplete propellant mixing on laser ignition. The ignition kernel growth process will be characterized by using laser shadowgraphy.

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## Instrumentation

### Failure Detection and Autocalibration of Piezoelectric Sensors

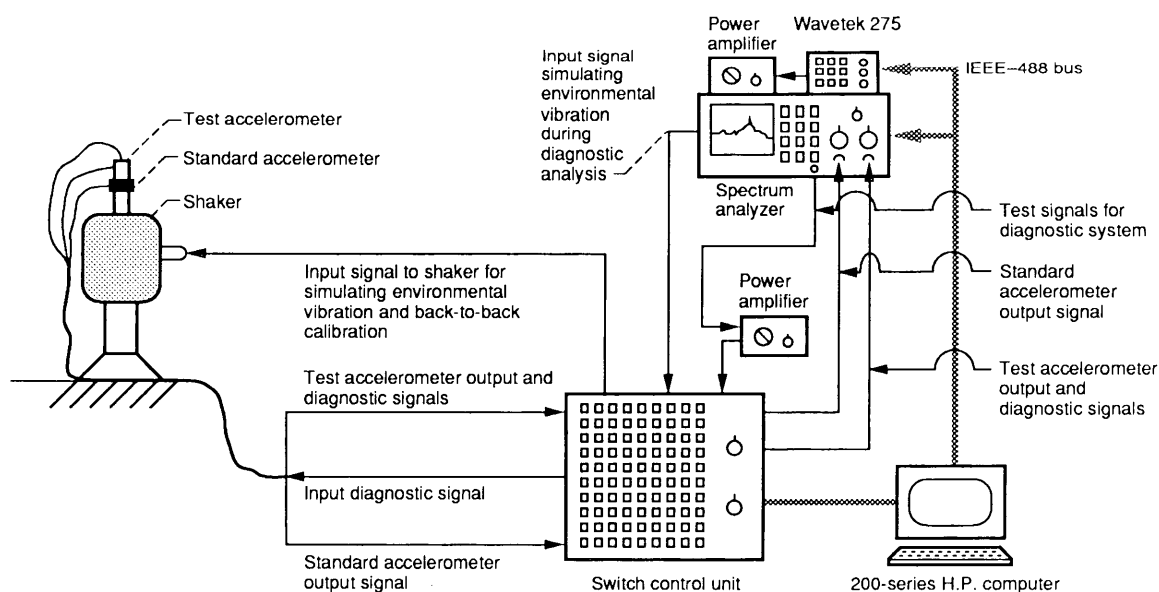
Large, complex systems such as the space shuttle main engines are now being instrumented with great numbers and diverse types of sensors to control and monitor engine health. It is increasingly difficult to check the accuracy and integrity of these sensors through traditional test and calibration techniques. Typically, sensor failures occur in the electronics, the sensing element itself, or the sensor mounting. These failures manifest themselves as "hard" failures such as broken wires or "soft" failures such as drift due to temperature changes. A failure detection and autocalibration technique would allow for in-situ evaluation and calibration of the sensor itself.

One means of detecting sensor failure is to provide a known input to the transducer and then observe the response. For piezoelectric devices an input could be generated by a miniature impact device incorporated into the sensor itself. When the device was triggered, the impact would produce a measurable response dependent on the health of the sensor element, the electronics, the mounting impedance, and the dynamic activity from other sources. Comparing the response with a known "good" response would provide information on the health of the transducer system.

NASA Lewis is supporting research to develop autodiagnostic and auto-

calibration technology for piezoelectric sensors. Under a grant to Cleveland State University an accelerometer incorporating this technology has been fabricated and is being tested. This technology, when incorporated into a vehicle health monitoring and control system, could improve safety, reliability, and cost effectiveness.

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Computer-aided test system for analyzing self-diagnostic piezoelectric sensor systems

# Facilities

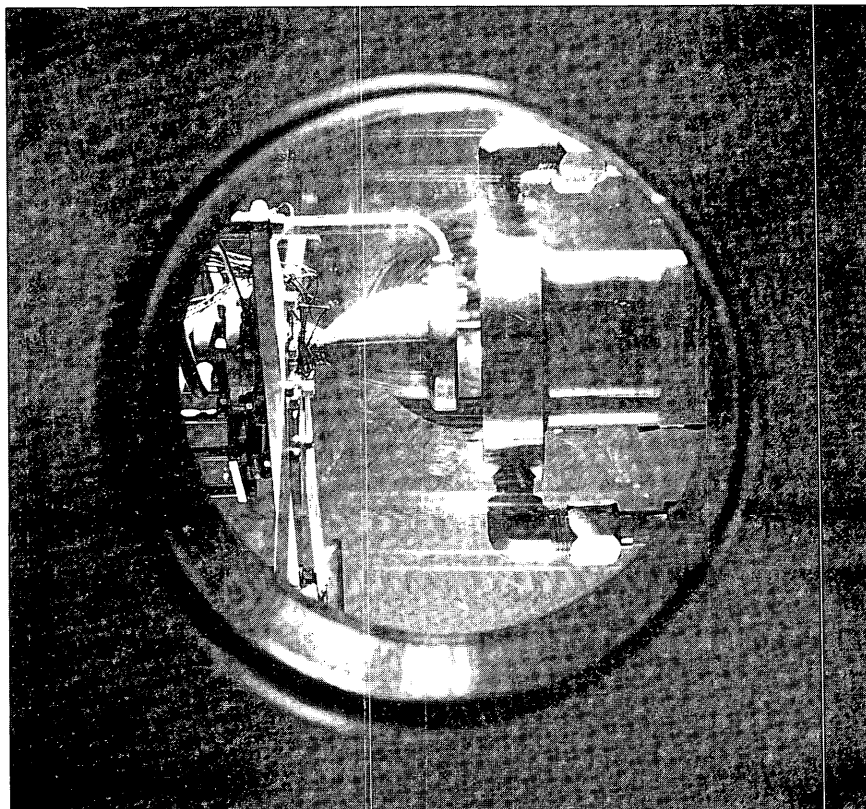
## Low-Thrust Chemical Propulsion Research Facility

NASA Lewis has on-going programs on low-thrust chemical propulsion. Contract technology programs on small hydrogen-oxygen rockets resulted in their selection for use on Space Station *Freedom*. To complement the program, a new in-house research facility was designed and put into operation in 1989. The facility, located in the Rocket Laboratory, can accommodate steady-state or pulsed operation of gaseous hydrogen-oxygen rockets at thrust levels to 200 N. An altitude test chamber enables testing down to pressures of 0.2 psia. The vacuum is achieved via a two-stage air ejector and pressure recovery across a diffuser during rocket firing. The facility provides for real-time display of data and calculated performance values, storage of data on floppy disks, thrust measurements, thermographics, and Rayleigh and Raman spectroscopy. It was designed to be highly flexible, to provide quick turnaround, and to require a minimum number of personnel for operation. Testing requires only two on-site personnel and only 3 to 5 min between individual rocket firings. Depending on the testing requirements the facility can be turned around to test different types of test articles in approximately 1 week.

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*Low-Thrust Chemical Propulsion Research Facility*

## High-Reynolds-Number Heat Transfer Rig

A large body of data on flow and heat transfer over airfoils at the normal operating range of conventional gas turbines is available in the open literature. However, little information is available for the high Reynolds numbers at which the space shuttle main engines (SSME) operate (viz  $8 \times 10^6$ ). This information will be obtained from tests performed in a special heat transfer rig at NASA Lewis. Because the same rig also provides data at lower Reynolds numbers, the gap between high- and low-Reynolds-number regimes will be bridged. An additional objective is to determine the effect of turbulence on heat transfer at high Reynolds numbers.

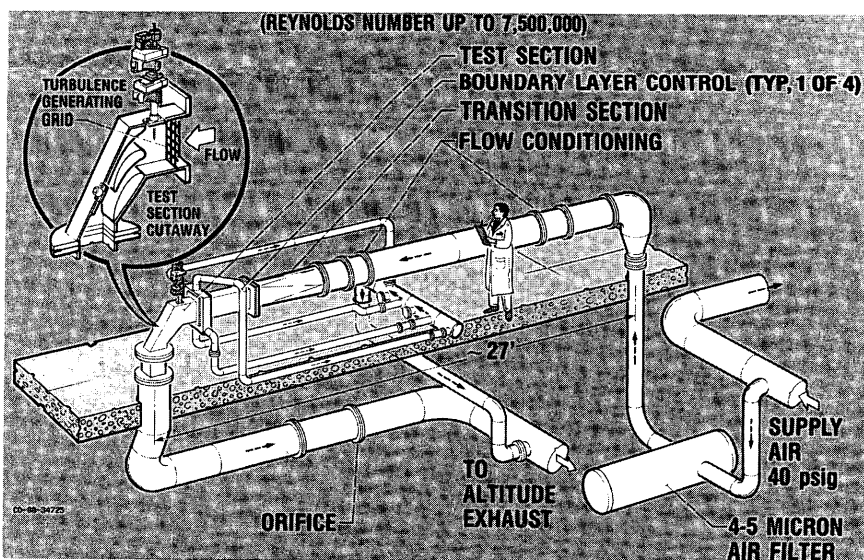
The rig consists of sections of stainless steel pipe that house flow-conditioning hardware such as perforated plates, screens, and honeycomb material. The boundary layer is bled off upstream of the test section to ensure a uniform velocity profile to the test blades. The test section, with a rectangular cross section, houses a test blade flanked by two partial blades to simulate the flow channels in the cascade. Turbulence is induced in the flow by a removable steel grid. Upstream of the test blade, a traversing disturbance generator is installed to simulate blade passing so that its effect on heat transfer can be observed.

Three test blades will be used during different phases of testing. An aluminum blade instrumented with static pressure taps will be used to map the steady-state flowfield around the blade. A second blade made of foam board will be used to collect heat transfer data. This blade is coated with liquid crystals on a

thin Inconel foil. The liquid crystals change color when the foil is heated, thus providing a general temperature profile under flow conditions. The third blade is similarly constructed but will have quick-response temperature sensors sputtered onto a Kapton sheet, which in turn is attached to the Inconel sheet.

The rig was installed in June 1989, and testing is expected to continue through December 1989.

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*High-Reynolds-number heat transfer rig showing major components and test blade configuration*



## Spacecraft Propulsion Research Facility

The Spacecraft Propulsion Research Facility (B-2) at Plum Brook Station was partially reactivated to support SPEAR I and EXCEDE III flight hardware testing for the Defense Nuclear Agency. The reactivated portion of the facility consists of a large space environment simulation chamber 38 ft in diameter by 55 ft tall. The chamber was successfully pumped down to  $2 \times 10^{-6}$  torr during the SPEAR I tests. The capability for operating at vacuum with xenon or argon plasma to more accurately simulate low-Earth-orbit conditions was recently added. The chamber then operated at  $1 \times 10^{-5}$  torr with  $1 \times 10^5$  particles/cm<sup>3</sup> xenon plasma density. The chamber is also equipped with a liquid-nitrogen cold wall and quartz lamp solar heat simulation capability.

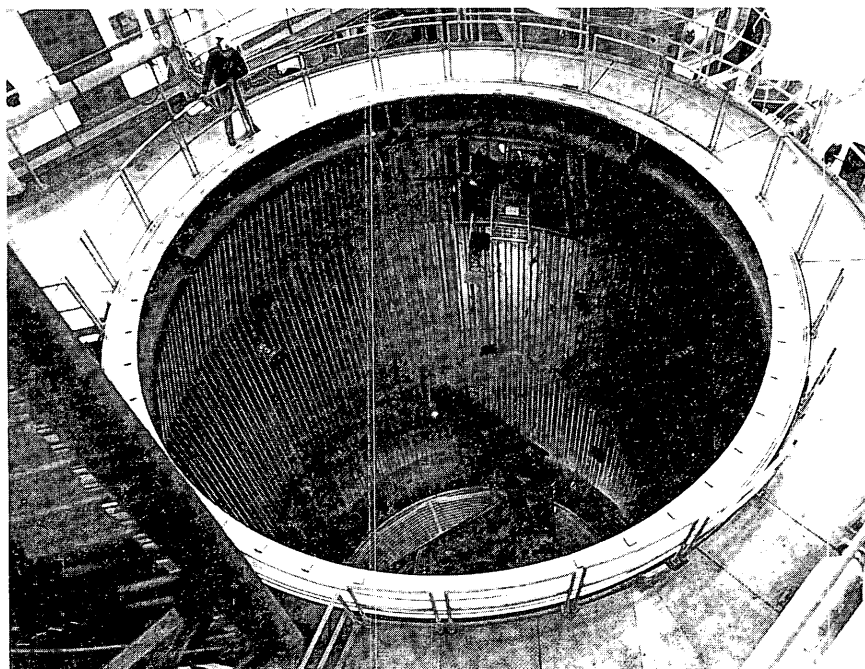
The facility was originally designed and built to test rocket engines up to 100,000 lbf in a simulated space environment. From 1968 to 1973 more than 50 hot firings of the Centaur rocket were conducted in the B-2 facility under simulated thermal-vacuum space conditions.

A feasibility study is currently in progress to assess the reactivation requirements for the other systems needed for rocket engine testing, such as the water spray chamber for cooling the rocket exhaust gases and the steam ejector system for maintaining the high-altitude condition during firings. The facility is being considered for rocket engine development work in support of Project Pathfinder as well as for structural testing of the national aerospace plane with liquid hydrogen.

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*Test chamber of B-2 facility*



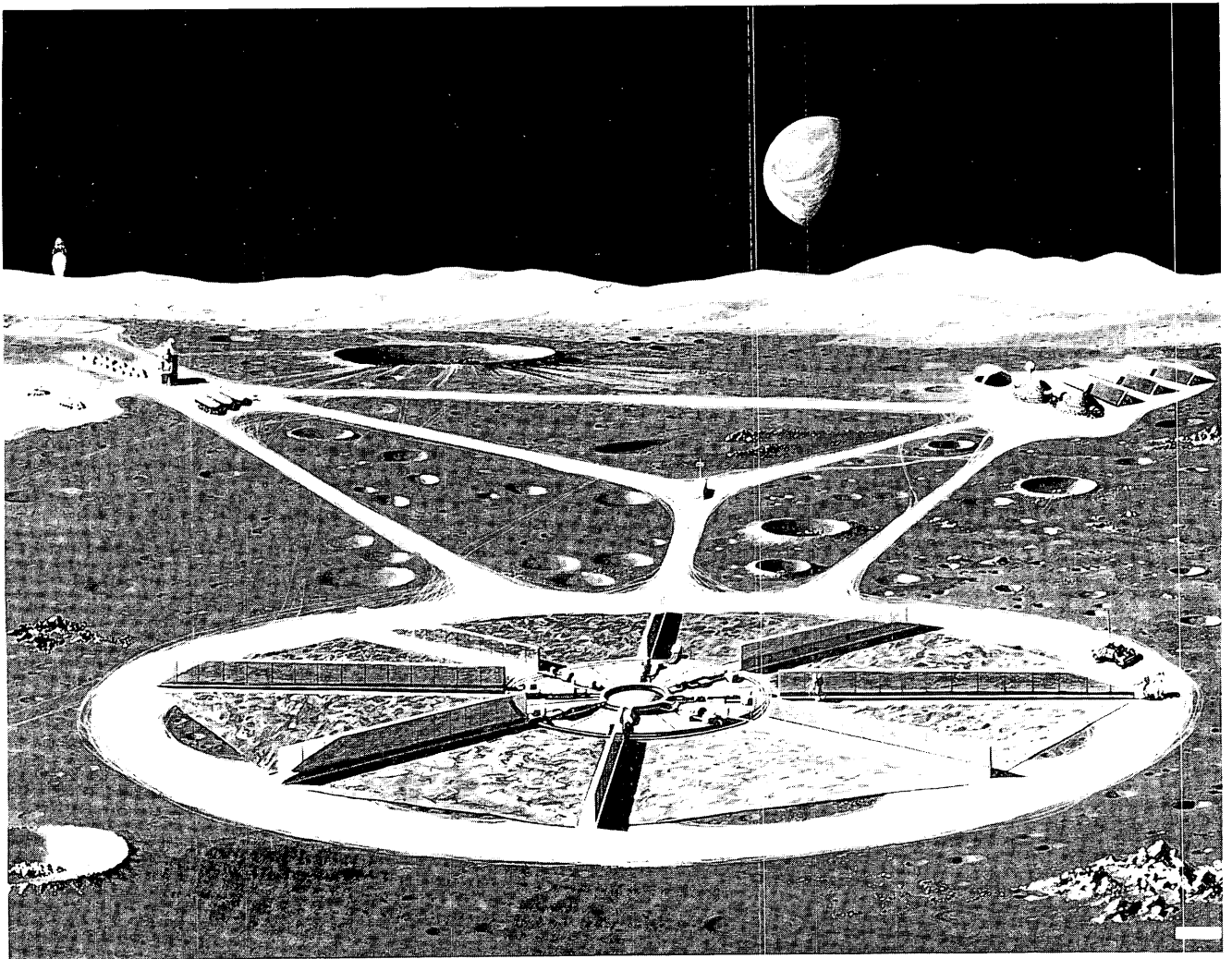
### **Combustion Air to Rocket Engine Test Facility**

The NASA Lewis Rocket Engine Test Facility (RETF) complex is a stand-alone facility dedicated to rocket combustion research. The complex includes two major buildings along with extensive support services and is the only complex at Lewis capable of operational rocket testing. The RETF is designed for both sea-level and altitude testing of rocket engines.

Initially, the RETF's altitude test stand used a blowdown ejector system powered by gaseous nitrogen as the motive fluid to create a vacuum. This limited the total run duration at maximum thrust to approximately 5 min and required overnight repumping before the next altitude test could be run. The addition of the new combustion air line, along with new ejectors, now permits continuous altitude testing and thus has greatly increased the productivity of this important research facility.

In modifying the combustion air system, combustion air piping was extended from an existing line to the RETF area. The new section of pipeline is approximately 2200 ft long and 24 in. in diameter. The original ejector system was replaced with new ejectors specifically sized to run with 150-psig combustion air as the motive fluid.

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# Space Power

## Strategic Objectives

- To remain in the forefront as the NASA center for space power systems research, technology, and development in order to meet current and future national needs.
- To successfully develop the space power systems for Space Station *Freedom*.
- To be the NASA center responsible for the development of all future space power systems that require advances in technology and are first of a kind.

# Programs

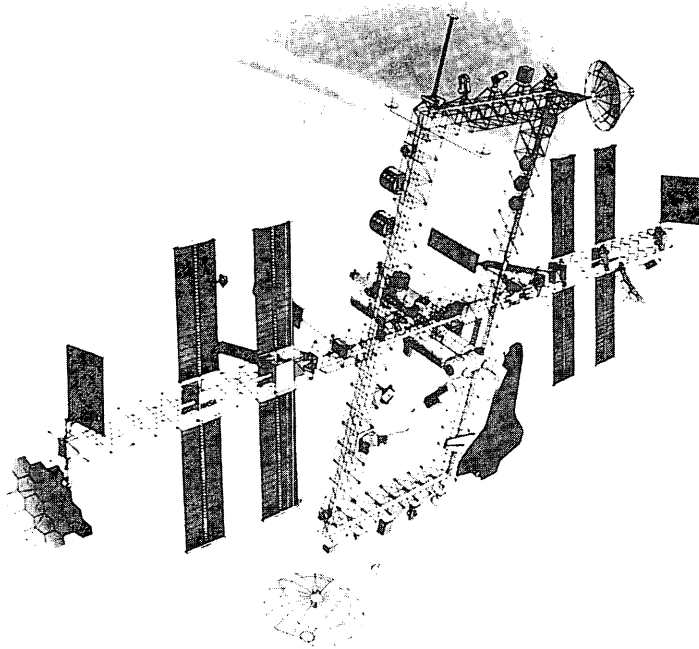
## Space Station *Freedom*

NASA Lewis is responsible for managing the design, development, and future operations of the electric power system for Space Station *Freedom* and its two platforms. This includes the end-to-end power system from power generation and storage to power management and distribution and the conversion of power for users. The power system presently consists of 75 kW of photovoltaic arrays and nickel-hydrogen batteries for the first phase of power generation and storage, with the first launch of 18.75 kW planned for 1995. The power will be distributed via a high-voltage ac/dc distribution system. A decision is planned in 1990 on the second phase of the Space Station Program. The second phase will include the addition of 50 kW of solar dynamic power generation with thermal storage.

In addition to managing the prime contractor (Rocketdyne Division of Rockwell International) for the power system development, Lewis also manages supporting tasks to reduce potential power system risks in areas in which Lewis has particular expertise. Lewis also supports the planning for the utilization and evolution of the space station. Lewis has signed a cooperative agreement with the NASA Johnson Space Center to support them in developing the space station propulsion system.

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*Artist's concept of Space Station Freedom*

## SP-100 for CSTI High-Capacity Power

The SP-100 Program was jointly established in 1983 by the Department of Defense, the Department of Energy, and NASA to develop the technology necessary for military and civil space nuclear power systems. In 1986 the SP-100 Program started a multiyear Ground Engineering Systems (GES) Development Project to design, develop, and demonstrate at ground test sites the operation of the major subsystems of a 100-kWe nuclear-thermoelectric power system. The generic flight system design was completed by the GES contractor (General Electric) in mid-1988.

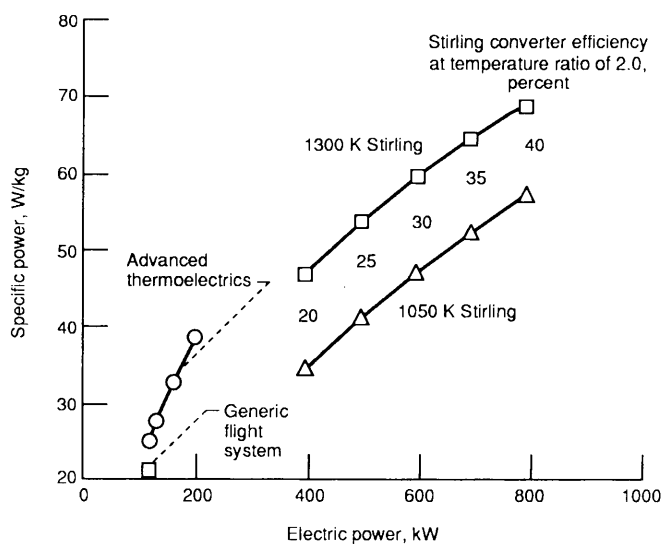
During fiscal 1986 and 1987 the NASA SP-100 Advanced Technology Project was devised to maintain the momentum of promising technology advancement efforts started during phase I of SP-100 and to strengthen, in key areas, the chances for successful development and growth of space nuclear reactor power systems for future space applications.

In fiscal 1988 the Advanced Technology Project was incorporated into NASA's new Civil Space Technology Initiative (CSTI). CSTI was established to provide the foundation for technology development in automation and robotics, information, propulsion, and power. The CSTI High-Capacity-Power Program also builds on the technology efforts of the GES project and provides a bridge to NASA's Project Pathfinder, started in fiscal 1989. Pathfinder's purpose is to further develop emerging innovative technologies that will allow a range of missions focusing beyond Earth orbit into the solar system, such as establishing a lunar outpost and transporting humans to Mars.

The goals of CSTI high-capacity-power development include advances in conversion systems, thermal management, power management, system diagnostics, and environmental interactions in order to significantly increase power densities from the 20 W/kg presently envisaged for the 100-kWe GES system. Advanced thermoelectric materials are projected to increase specific power from 20 W/kg to about 40 W/kg while approaching 200-kWe output. Development of free-piston Stirling power conversion and advanced radiators could further increase specific power to 70 W/kg and output to 800 kWe for the GES

2.4-MWt reactor. Technology advancement in all areas, including advanced materials, is required to ensure high reliability and the 7- to 10-year life demanded for future space nuclear power systems. The overall program will develop and demonstrate the technology base for a wide range of modular power systems with all these attributes plus mission independence from solar and orbital attitude requirements.

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SP-100 Stirling and thermoelectric performance predictions

## Pathfinder—Surface Power

The objective of the Pathfinder Surface Power Program, simply stated, is to develop solar-based power technology to a level of readiness sufficient to enable or enhance extraterrestrial surface missions. NASA's planning for the future exploration of the solar system includes precursor piloted missions and outposts as well as bases on the Moon and Mars. Supporting human expeditions to, and operations on, the surfaces of the Moon and Mars represents a substantial technology challenge for current and projected power system capabilities. The high levels of power associated with an operational base will require reactor power systems. During the installation of these permanent reactor systems, power systems based on solar energy will supply the needed power. Solar-based power systems will also be required to augment and serve as a backup power source for the reactor-powered base.

The thrust of the Surface Power Program is to develop a focused technology base in the areas of solar power generation, electrochemical energy storage, and electric power management capable of delivering 25 kW of reliable user power. Advances in amorphous silicon photovoltaic cell and blanket technology will be directed at meeting the 300-W/kg (air mass zero) performance target of this project. Photovoltaic blankets fabricated from amorphous silicon cells placed on flexible substrates supported by novel low-mass structures are compatible with low-volume stowage and low-mass requirements. However, the performance of amorphous silicon

cells must be upgraded to meet surface power requirements for stability, longevity, and efficiency.

Photovoltaic cells presently have a demonstrable specific power of 60 to 150 W/kg (air mass zero). The 1/6 to 1/3 g loadings anticipated on the Moon and Mars, respectively, plus the wind loadings on Mars require new robust concepts to be developed and verified. The unique environment of settling and driving dust, extended dormancy periods, and radiation and temperature extremes requires novel structural concepts as well as abatement techniques.

Hydrogen-oxygen regenerative fuel cell electrochemical energy storage systems offer a potential twentyfold increase in specific energy over state-of-the-art energy storage technologies. This is especially evident for the long-duration storage associated with lunar applications. Commensurate with the need for higher temperature, long-life autonomous and efficient operation of electrolyzer and fuel cell stacks are requirements for efficient and reliable thermal, gas, and liquid management technologies. The technological issues of material compatibility, gaseous and liquid storage and transfer, and thermal management must be identified, quantified, and resolved.

The technology of electric power management, the subsystem that ties power generation and energy storage to the load and to each other, has seen substantial advances due to the requirements of Space Station *Freedom*. However, to meet the goals of the Pathfinder Surface Power Program, the electric power

management subsystem requires a 50-percent reduction in mass at an acceptable life and reliability. The implementation of fault-tolerant and high-power-density electronics will allow conceptualization of a 55-kg/kWe electric power management subsystem.

In summary, advancing the technologies of electrochemical energy storage and photovoltaic power generation and coupling their performance with an advanced low-mass, reliable electric power management subsystem can lead to surface power systems having a reliable life of over 20,000 hours with system specific powers of 3 W/kg for lunar applications and 8 W/kg for Martian applications. System mass reductions coupled to the expected factor-of-10 increase in life will enable extraterrestrial surface missions where life, mass, and volume are driving forces for success.

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# Research & Technology

## Materials

### Carbide-Strengthened Niobium Alloy for CSTI High-Capacity Power

The Civilian Space Technology Initiative (CSTI) was established to provide the foundation for space power technology development. A major stone in that foundation is advanced materials to ensure high reliability and the 7- to 11-year (60,000 to 100,000 hr) life demanded for space nuclear power systems and to meet the stringent size, weight, and performance requirements of near-term and future systems. The niobium -1 percent zirconium alloy chosen as the material to demonstrate the SP-100 nuclear power system displays many properties suitable for such systems. However, it lacks sufficient creep strength to afford high reliability for the times and temperatures of current designs. Alloying Nb-1Zr with 500 to 1000 weight parts per million (wt ppm) of carbon significantly increased creep strength for the base material. This carbide-particle-strengthened material is called PWC-11.

Both electron-beam-welded and unwelded PWC-11 were creep tested from 1350 to 1450 K in a vacuum, and the results were compared with the similarly tested Nb-1Zr alloy. Annealed PWC-11 was more creep resistant than similarly annealed Nb-1Zr by at least a factor of 3 in applied stress over the current SP-100 space power design criteria. The electron beam weld region of PWC-11 was consistently stronger in creep resistance than the unwelded PWC-11 base metal tested at 1350 and 1400 K. The (70ZrC-30NbC) face-centered-cubic monocarbide was the only extracted phase identified after high-temperature exposure of

the PWC-11 material and did not appear to overage. The monocarbide is believed to be extremely stable in the presence of liquid alkali metal reactor coolants. Creep tests on PWC-11 at 1350 K and stress levels about twice the expected service life stress have not exhibited any creep strain at times exceeding 30,000 hours, whereas Nb-1Zr will have achieved almost 4-percent creep strain.

Research is continuing on the characterization of the strength properties and the stability of the strengthening carbide phase of PWC-11 as affected by composition and fabrication processing.

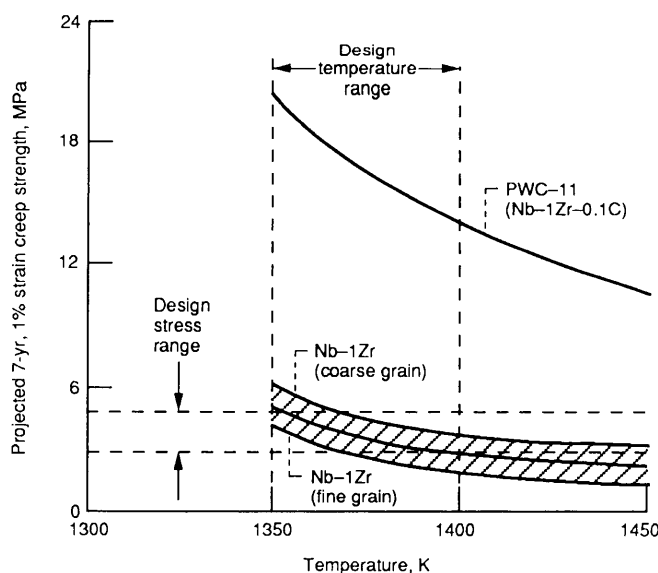
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Titran, R.H.; Moore, T.J.; and Grobstein, T.L.: Creep Behavior of Niobium Alloy PWC-11. NASA TM-89834, 1987.

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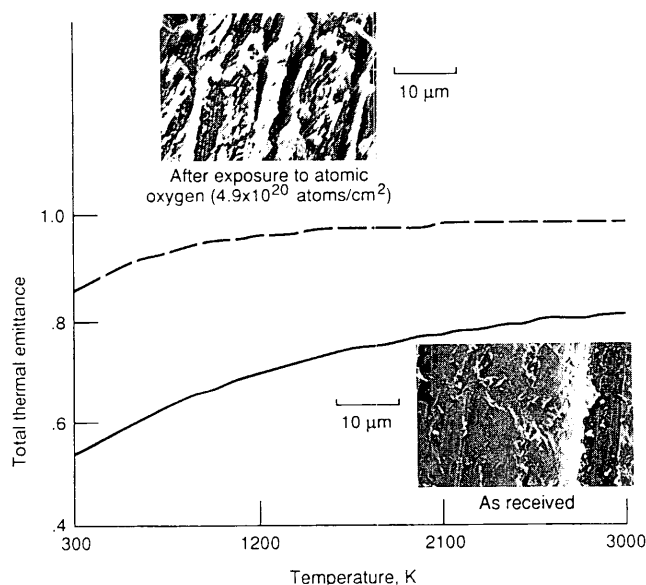
Projected temperature and creep strain potential for PWC-11 and Nb-1Zr

## Carbon-Carbon Composites for High-Thermal-Emittance Radiator Surfaces

Carbon-carbon composites are under consideration for space nuclear power system radiators because of their high thermal conductivity, light weight, and high strength. Increasing the thermal emittance of these composites can result in further weight savings for the spacecraft by reducing the area needed for thermal transport. A surface with morphological features larger than the wavelength of the emitted radiation can be an efficient radiator of thermal energy. For example, roughening the surface of a carbon-carbon composite will allow it to become a better thermal emitter.

Surface roughening has been observed on carbon samples exposed in the low Earth orbital environment to ram-oriented atomic oxygen. The surface of the carbon develops high-aspect-ratio cones as it reacts with atomic oxygen. This texturing effect can be simulated on Earth by using a directed atomic oxygen ion beam at an energy of approximately 57 eV in vacuum. Untreated carbon-carbon composites have thermal emittances as low as 0.38. Thermal emittances greater than 0.85 (at operating temperatures between 500 and 900 K) have been achieved on carbon-carbon composites after texturing. Thus, texturing significantly improves thermal transport capability.

At spacecraft operational altitudes above approximately 600 km the concentration of atomic oxygen is low enough so that a carbon-carbon composite radiator textured in a ground-based system would be able to maintain its thermal emittance as well as its structural integrity over missions of 10 years duration.



*Thermal emittance of carbon-carbon composite radiators*

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### Elimination of Print-Through in Solar Dynamic Concentrator Surfaces

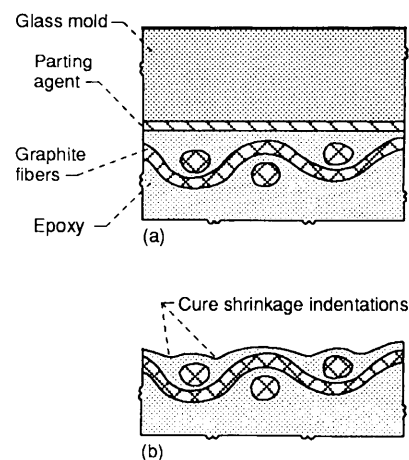
Highly reflective, accurately contoured mirrors are needed for solar dynamic space power systems. Graphite fiber/epoxy composites are attractive candidates for such applications because of their low mass and tailored thermal expansion. However, the goal of high specularity is hindered by a phenomenon called print-through, where the weave of the underlying graphite fabric is transmitted to the surface. The print-through problem can be traced to the 2- to 6-percent shrinkage that occurs when most epoxies are cured.

Composite mirrors are prepared in a glass mold to obtain the smooth surface for the mirror finish. Epoxy-rich and epoxy-poor regions are located between the graphite fabric and the glass mold. The epoxy-rich regions may shrink more than the epoxy-poor (high graphite fiber content) regions, resulting in surface distortion, or print-through. Print-through is not limited to fiber/epoxy composites. A thin aluminum or microsheet-glass facesheet attached with epoxy to a honeycomb substrate also suffers from print-through. In this case print-through can be traced to the shrinkage of the epoxy fillets holding the facesheet to the honeycomb substrate.

Novel expanding monomers have been identified, such as nobornane spiro-orthocarbonate, that undergo a dissolution followed by a ring opening reaction, resulting in an overall expansion during polymerization of about 17 to 19 percent. A mixture containing the appropriate ratio of expanding monomer and conventional epoxy resin should yield a polymer matrix with nearly zero shrinkage

upon curing. Such monomer systems are currently being evaluated to determine their effectiveness in minimizing fabric print-through in solar dynamic composite concentrator surfaces.

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Print-through: (a) precure, (b) postcure.

## Advanced Thermal Energy Storage Material

Space solar dynamic power systems require that thermal energy be collected and stored during the sunlit portion of the orbit to provide power to the engine during the shade portion of the orbit. All solar dynamic power systems proposed to date use one of the fluoride salts such as lithium fluoride or a eutectic of fluoride salts such as lithium fluoride/calcium fluoride for this purpose. These materials characteristically have low density and extremely low thermal conductivity. In a power system the heat is removed rapidly from the thermal energy storage material. The thermal conductivity must therefore be enhanced. This can be done by either providing fins into the salt or by embedding a good conductor such as graphite fibers into the salt. However, both of these solutions add weight to the overall system.

NASA Lewis began a program at the Oak Ridge National Laboratory (ORNL) to search for a thermal storage material with both high conductivity and high density. Germanium has both of these important qualities, but in the molten state it is corrosive to other metals. Oak Ridge has determined that nuclear-grade amorphous graphite is compatible with germanium and is a possible container material. Six hundred heating cycles have been run on this combination. The cycles are 1 hour at 773 K, 30 min heating, 2 hours at 1273 K, and 40 min cooling to 773 K. No degradation of the container was observed after the tests. It was also experimentally determined that 0.5 percent silicon added to the germanium promotes wetting of the graphite walls. Compatibility tests are being

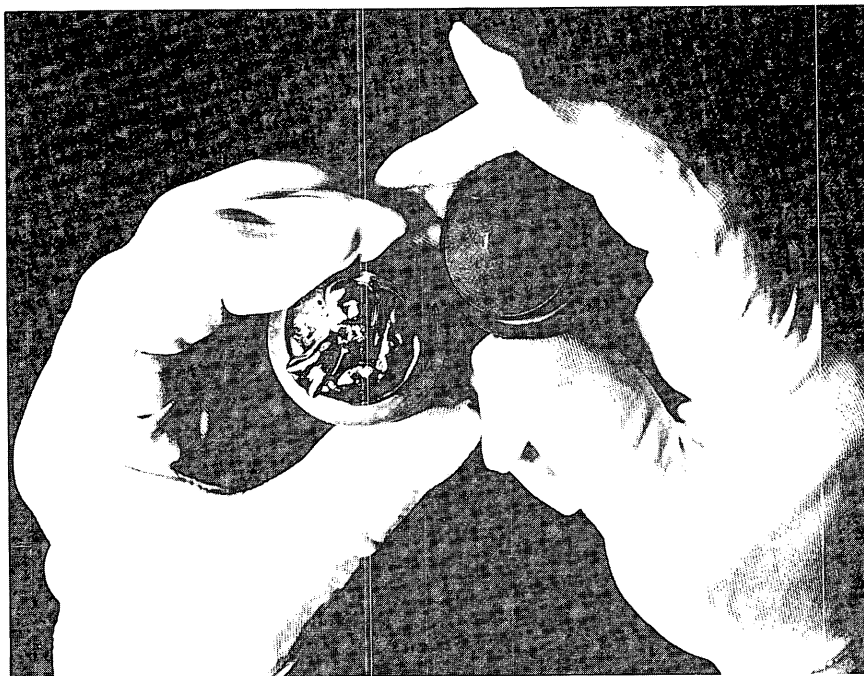
conducted on another candidate container material, boron nitride.

The search for high-conductivity thermal energy storage materials will continue with the investigation of other high-density metal systems. NiSi and NiSi<sub>2</sub> are possible candidates. Work will proceed on the germanium material with a study of boron nitride compatibility.

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*Thermal energy storage test capsule—graphite container filled with germanium*

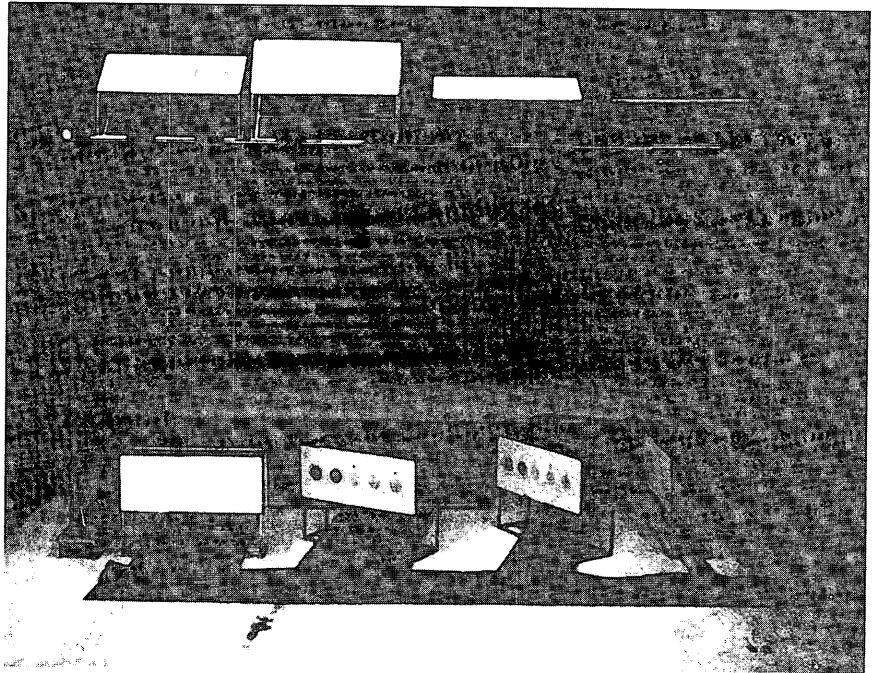
## Durability of Surface Power Systems in Martian Environment

Space power system components such as photovoltaic arrays, radiators, solar concentrators, and power components are vulnerable to degradation in the Martian environment. The natural environmental characteristics of Mars—winds, dust, ultraviolet radiation, temperature, soil, and atmospheric condensates—may pose a threat to surface power systems. Accumulation of dust particles (2 to 10  $\mu\text{m}$ ) may reduce the transmittance of photovoltaic arrays or reduce the thermal emittance of radiators, thus degrading their performance. The deleterious effects of dust or saltation (movement of dust by the Martian wind) may also be enhanced by electrostatic charges resulting from dust and sand abrasion of power surfaces.

NASA Lewis is evaluating the effects of saltation particles, dust deposition, and potential abatement techniques on photovoltaics and radiator surfaces. The tests, being conducted at the Martian Surface Wind Tunnel at NASA Ames Research Center, evaluate dust deposition and removal for various thin-film coatings on photovoltaic coverglass samples as a function of orientation, angle of attack, and elevation. Simulating the Martian environment allows us to evaluate its impact on power system components and to devise strategies to harden these components.

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*Photovoltaic coverglass samples being evaluated in Martian Surface Wind Tunnel*

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## Life Prediction

### Thermal Cycle Testing of Space Station *Freedom* Solar Cells

NASA Lewis is conducting thermal cycle tests to demonstrate the durability or operational life of the solar array welded-interconnect design in a low-Earth-orbit thermal cycling environment. Secondary objectives include observing and identifying potential failure modes and any effects of thermal cycling on solar array blanket coupons.

Power for Space Station *Freedom* will be generated by four photovoltaic power modules, each with two solar array wings. Each solar array wing has two blankets, or assemblies, of active solar cell panels. An active solar cell panel contains 200 solar cells, each connected to the underlying copper circuit by 10 welded contact points. These solar-cell-to-circuit interconnects are subjected to thermally induced stresses during temperature excursions experienced in every orbit. *Freedom* will orbit the Earth approximately once every 90 min—6000 thermal cycles a year or 90,000 thermal cycles over a period of 15 years.

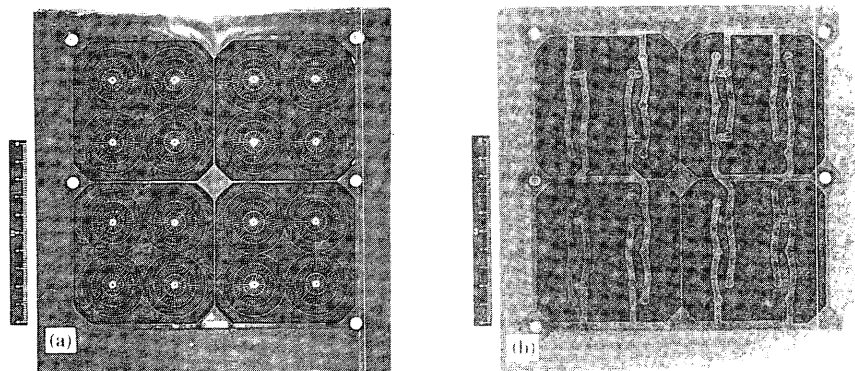
Lewis is presently testing solar array blanket coupons in a thermal cycling chamber between  $-90$  and  $70$  °C in a dry nitrogen environment. The coupons are cycled at an accelerated rate and are removed at equivalent low-Earth-orbit lives for electrical performance measurements and visual inspections.

The test articles were supplied from the Photovoltaic Array Environmental Protection (PAEP) Program by the Lockheed Missiles and Space Company. Four thermal cycle coupons were fabricated by using the same panel design, materials,

and manufacturing processes that are presently the baseline for Space Station *Freedom*. To date, 48,000 cycles have been successfully completed without any measurable electrical degradation.

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Solar array thermal cycle coupons: (a) front, (b) back

## Power Systems

### Electromechanical Actuation and Integrated Electric Power for Advanced Launch System

In order to attain the advanced launch system goal of reduced life-cycle costs and improved operational efficiency, significant reductions must be made in the launch operations and servicing requirements. NASA Lewis is working to develop and demonstrate the needed technologies and to assess alternatives. One way to achieve the goal is by using electromechanical actuation integrated with a single vehicle electric power system and controls for all actuation and avionics requirements. This would eliminate centralized hydraulics, auxiliary power units, ground support carts and equipment, and the associated excessive manpower-intensive testing and qualification procedures. This ongoing effort is being supported by a combination of in-house developments, grant work at the University of Wisconsin (Madison), and two prime contractors, General Dynamics Space Systems Division and Boeing Aerospace Corporation.

Recent advances in power control and high-frequency distribution systems make an all-electric approach attractive. Multikilowatt variable-voltage, variable-frequency power has been synthesized from 20-kHz power by using pulse population modulation. Operation of a 2-hp, 400-Hz induction motor for both motoring and generating with full control has also been demonstrated. While the motor is running at constant speed, the torque can be instantly reversed, resulting in the machine switching from the motoring to the generating mode. The design and fabrication of second-generation control electronics have been completed. The electronics

have also been redesigned by incorporating embedded microprocessors to allow simplified control interfaces and to provide local intelligence. Embedded microprocessors and smart components with health monitoring will enable distributed system intelligence and fault-tolerant architectures in the power and avionics systems.

With a team effort, control design expertise will be supplied to build a 25-hp dynamometer test stand for motor control evaluation and technology demonstration. An effort will also be made to design, build, and test two 20- to 25-hp motor controllers capable of driving induction or permanent magnet machines, or both. Additional tasks will acquire advanced power semiconductors and other critical power system components along with integrated power breadboards having distributed intelligence, control, redundancy, and protection.

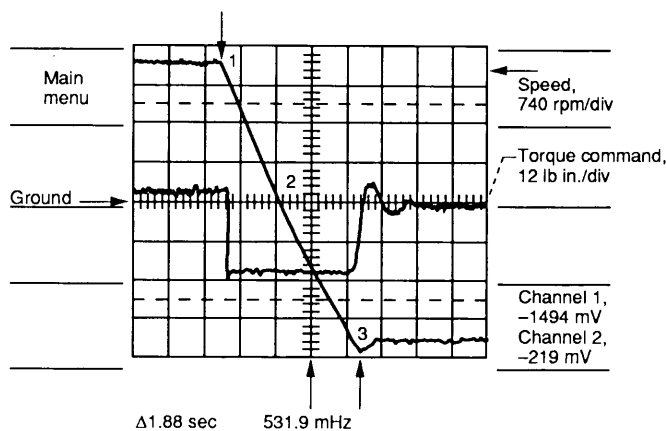
Technology from these tasks appears attractive for use on expendable launch vehicles and in commercial and military aeronautics applications. In addition, several diverse industries are interested in the potential payoffs of the advanced alternating-current motor controller for actuation and other processing operations.

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Speed reversal of 2-hp induction motor

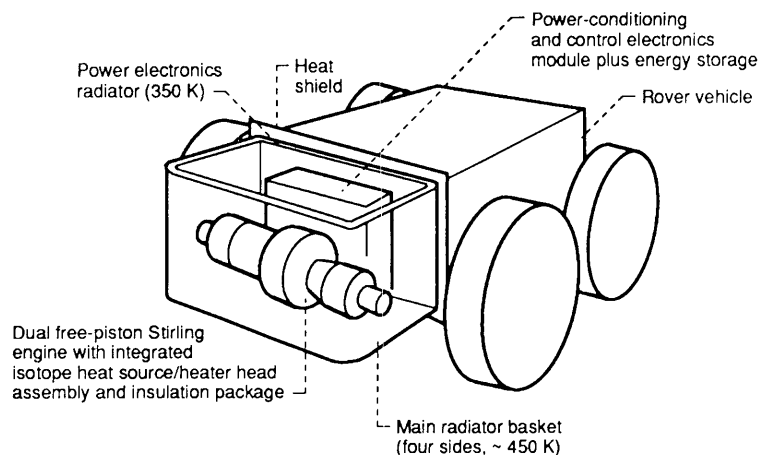
## Power Systems for Mars Rover Sample Return Mission

NASA Lewis has compared four isotope power system concepts for supplying onboard primary electric power to an autonomous planetary rover vehicle. A representative design point corresponding to the preliminary requirements for the Mars Rover Sample Return Mission (500 W) was selected for comparison purposes. All system concepts utilized the general-purpose isotope heat source (GPHS) developed by the Department of Energy. Two of the concepts employed thermoelectric conversion: a reference case using the GPHS radioisotope thermoelectric generator (RTG), and the other using an advanced RTG with improved thermoelectric materials. The other two concepts employed dynamic isotope power systems: one using a closed Brayton cycle turboalternator, and the other using a free-piston Stirling cycle engine/linear alternator with integrated heat source and heater head. Near-term technology levels were presumed for concept characterization, and component technology figure-of-merit values were taken from the published literature. For example, the closed Brayton cycle characterization drew from the historical test data base accumulated from space Brayton cycle subsystems and components. Thermoelectric system performance was estimated from Voyager flight experience through performance estimates based on recent advances in thermoelectric materials under the SP-100 and CSTI programs. The Stirling dynamic isotope power system was characterized from scaled-down space power demonstrator engine data that incorporated the Department of Energy GPHS directly into the heater head.

The results differed from previous comparisons of isotope power for low-Earth-orbit (LEO) applications because the background temperature on the Martian surface is high relative to LEO and dynamic systems have higher sensitivity to elevated sink temperature. Although dynamic systems have historically shown advantages of lower specific mass and reduced isotope inventory per delivered electrical watt, the mass advantage of dynamic systems is significantly reduced for Mars rover application because of Mar's high background temperature.

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*Stirling dynamic isotope power system for Mars rover vehicle*

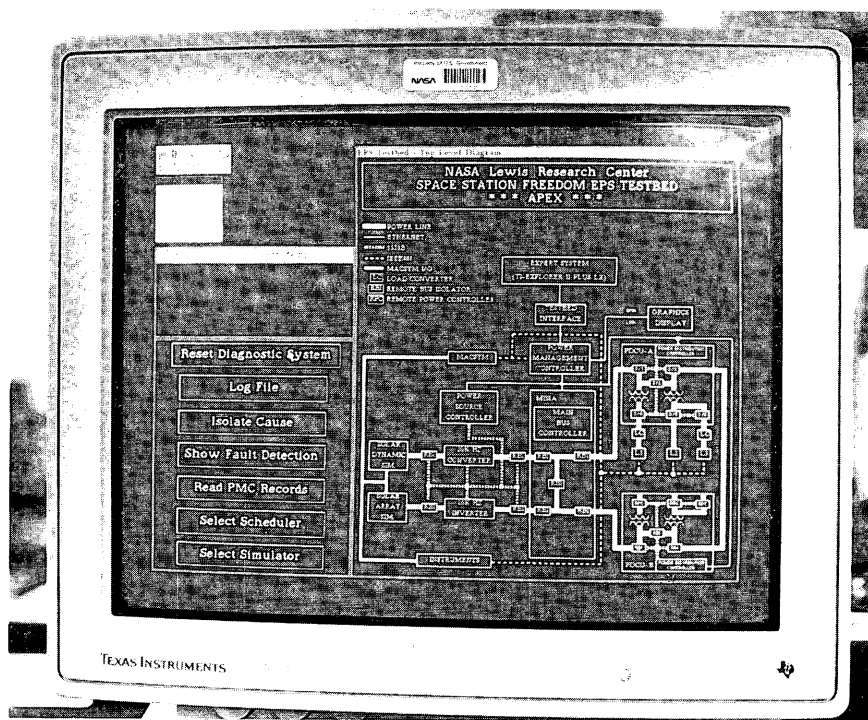
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### Autonomous Power Systems

NASA Lewis is engaged in a program to develop and demonstrate knowledge-based system software for the electric power system of the evolutionary Space Station *Freedom*. Applying artificial intelligence technology to large, complex space power systems will reduce maintenance and operating costs and improve overall reliability and crew safety. Although traditional automation approaches have been adequate for the preplanned, but complex, mission operations of the space shuttle and unmanned spacecraft, future automation systems clearly must be capable of adapting to uncertain operating conditions and environments and must perform cooperative problem solving both with humans and with other intelligent agents.

The initial Lewis effort is concentrating on the in-house development of a fault-management expert system that can assist system operators in detecting, isolating, and diagnosing power system fault conditions in real time. This "intelligent assistant" will later be extended to aid in reconfiguring and recovering failed power systems. Lewis is also developing approaches to power or load-scheduling systems that will enable efficient energy utilization while working in close conjunction with the fault-management module.

A first prototype version of the automated power expert (APEX) diagnostic expert system has been developed on an artificial intelligence workstation and will be demonstrated on a small power distribution breadboard. Subsequent plans call for demonstrating the system on the Space Station *Freedom* electric power management and distribution



APEX prototype on artificial intelligence workstation

testbed facility. This entails expanding the APEX knowledge base to include additional testbed information and developing a communications interface between APEX and the testbed control system.

A further goal is the development of electric power expert software capable of "deeper thought" reasoning to better handle more complex and perhaps unanticipated fault scenarios. It is also hoped that the automation technology experience gained from the Space Station *Freedom* power system can be extended to other large space power systems such as those for surface power or planetary exploration.

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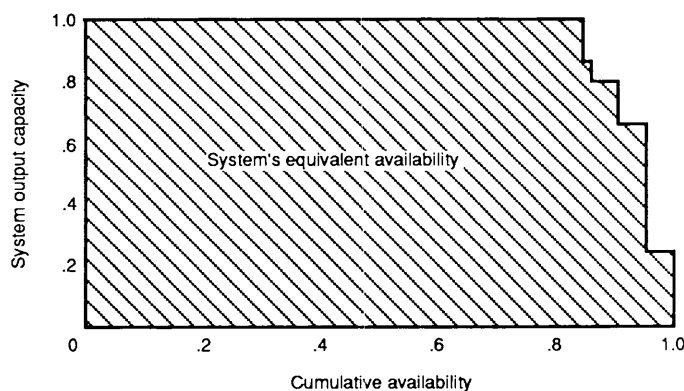
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## Reliability and Availability Modeling of Space Station *Freedom* Power System

A reliable power system for Space Station *Freedom* is critical to meeting safety and performance design criteria. To assess the reliability and availability of power system designs, a computer program called Event Time Availability and Reliability Analysis (ETARA) was developed. ETARA uses a statistical Monte Carlo method to simulate the failure, repair, and capacity states of components and subsystems throughout the life of the system.

Although written to assess power system designs, ETARA is completely general and can be used to model any system that can be represented by a block diagram of components in series or parallel combinations. Each block is characterized by a capacity, a failure rate distribution, and a mean time to repair. The types of analyses that can be performed with ETARA include availability, reliability with repair, and reliability without repair. Results include overall system availability, availability of partial capacity states, and average continuous time at each capacity state. The ability of ETARA to simulate partial capacity states is significant and not widely available in industry-standard reliability modeling tools.

ETARA incorporates a user-friendly, menu-driven interface with full-screen-input data entry and editing. It is written in the programming language APL2 and has versions to run on 386-based personal computers as well as mainframes running VM or MVS operating systems.



ETARA's graphical analytical results

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## Logistics Support Analysis of Space Station *Freedom* Power System

The Space Station *Freedom* electric power system will be designed to operate at its specified performance level indefinitely through a program of corrective and preventive maintenance. Because of the unique logistical challenges confronting the maintenance support of the space-based system, NASA Lewis has begun a logistics support analysis (LSA) process. The objective of a formal LSA process is to conduct a detailed parallel analysis, interactive with the engineering design and integration disciplines, to ensure that supportability considerations are incorporated into the electric power system design. Additionally, the LSA process will identify the requirements for acquiring logistics resources (technical data, spares, tools, support equipment, etc.) necessary to maintain and operate the system through its serviceable life.

The major contracted effort is by Rocketdyne under NASA Lewis technical management. This joint contractor-customer activity ensures clear communication concerning support needs and facilitates an orderly, controlled development of the integrated logistics support infrastructure. The LSA results will be documented and disseminated through several formal products.

A plan for documenting the LSA process has been developed and approved. Additionally, validated MIL-STD-1388-2A software called the Distributed Integrated Logistic Support Analysis (DILSA) has been installed at both Lewis and Rocketdyne. Included with the DILSA software are two companion software modules for front-end analysis. The DILSA program, a personal-computer-

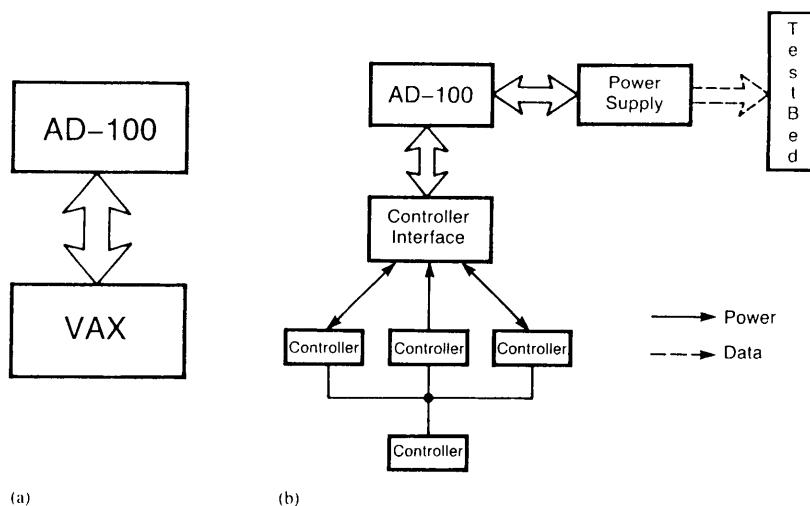
based system, will operate from a single master station and an unlimited number of networked PC workstations. The master station controls data access, input, and reporting. Its access control feature limits access to users assigned by the data base manager. Additional capabilities include backup of files on a VAX computer, nine-track tape generation for master file transfer, and data transfer from Rocketdyne to Lewis.

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## Real-Time Simulation of Space Station *Freedom* PMAD Testbed

A real-time simulation environment has been developed to allow evaluation and development of software used to control the Space Station *Freedom* power management and distribution (PMAD) testbed. A real-time simulation of the testbed is obtained by using a load flow analysis to provide all electrical network data. The load flow analysis is run on an AD 100 computer from Applied Dynamics, Inc., and the simulated data are outputted to an external computer running the supervisory control software. With this simulation facility, control algorithms can be rapidly evaluated and debugged before they are installed in the PMAD testbed. The real-time simulation software was written under contract to Lewis by the Rocketdyne Division of Rockwell International.

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Real-time simulation of PMAD testbed: (a) current configuration;  
(b) enhanced configuration

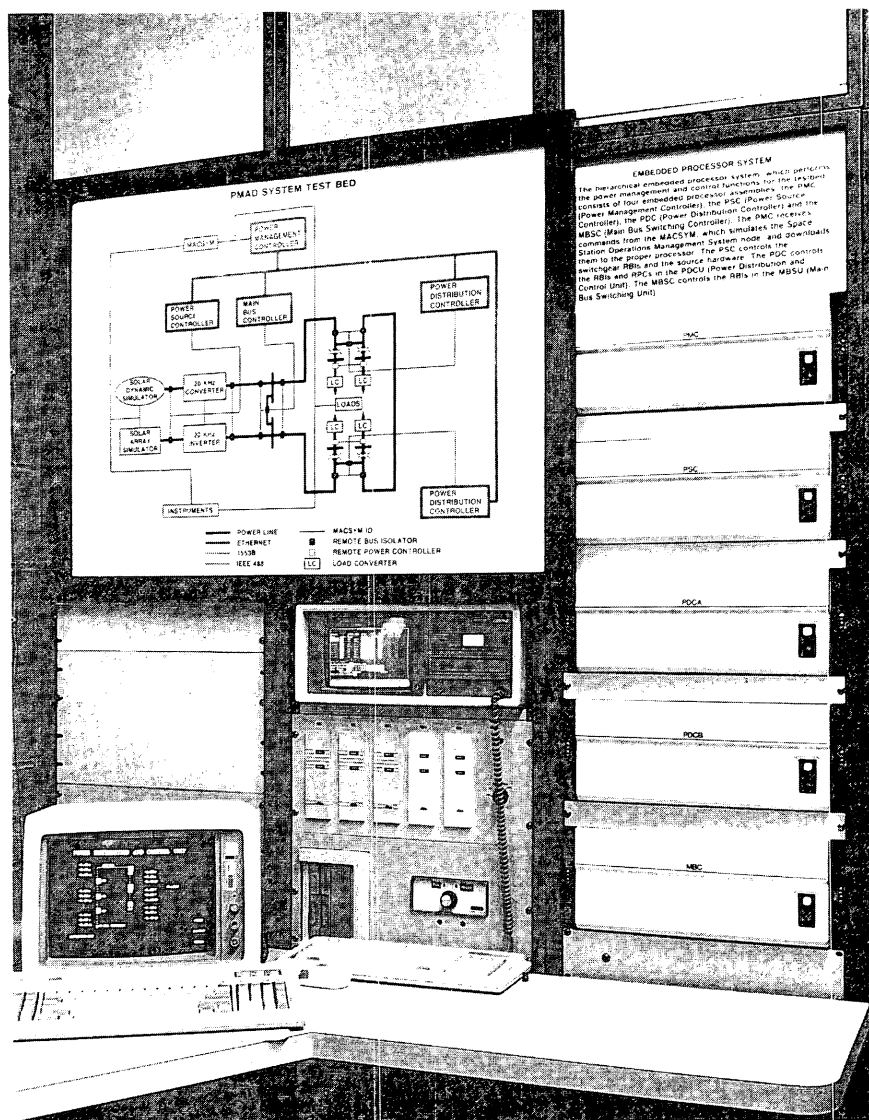
## Software Development for Space Station Freedom PMAD Testbed

Software has been developed, coded in Ada, and used in the power management and distribution testbed distributed-controller environment. The Ada programming language is used so that a flexible and maintainable environment is available for developing power system control algorithms. The software is used in the testbeds for both automatic and manual control.

The software design for the control computers uses an object-oriented design methodology and incorporates some of the advanced features of the Ada language, including tasking. The software is designed to be as generic as possible, allowing it to be used on any of the control computers with only minor modifications. Hardware-dependent portions of the design are encapsulated so that the software can be easily adapted to power system hardware developed in the future. Software support was obtained from Rocketdyne Division of Rockwell International.

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PMAD embedded processor system

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## Power Components

### High-Temperature Flexible Power Cable

The SP-100 nuclear reactor system requires a high-temperature, radiation-resistant power cable to deliver electric power from the isolated reactor to the spacecraft. The cable must be flexible for stowage and withstand a temperature of 450 °C. NASA Lewis has studied the options for insulating this cable. The environment is too severe for all known organic polymers, but several ceramic, oxide, and glass insulating materials are satisfactory. Flexibility is achieved by using the materials in the form of woven fibers and as thin flexible layers.

A basic cable design has evolved that uses a nickel-clad copper wire conductor, mica tape insulation, and woven glass outer sheathing. New England Wire has constructed a special power cable of high-temperature woven ceramic. Several versions of the ceramic cable were tested.

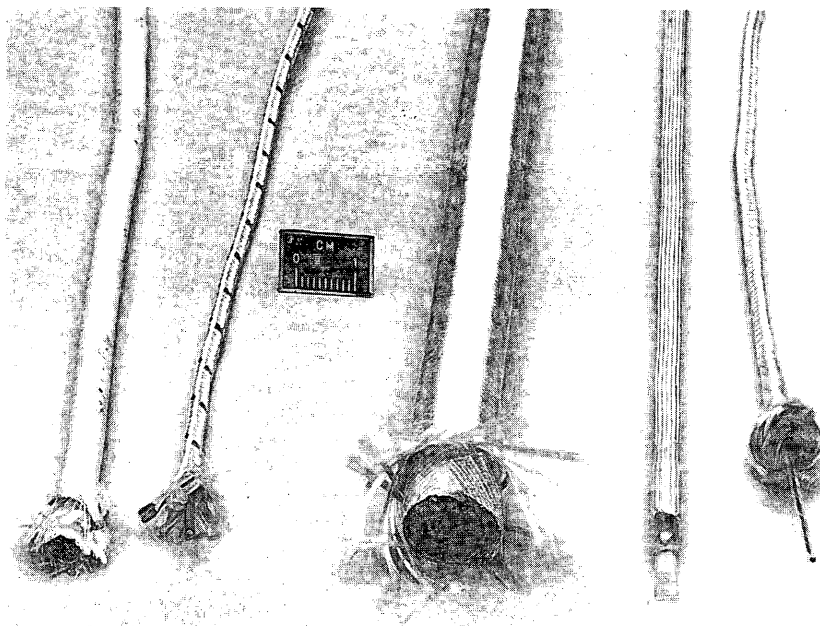
This type of cable construction has been chosen for the design of the SP-100 ground engineering tests, but it is limited to low-voltage operation. New techniques will be required for advanced high-voltage power distribution systems.

In order to avoid the possibility of catastrophic forms of breakdown during higher voltage operation, the cable will be operated with its insulation exposed to the environment, eliminating the metallic outer ground shield. In low Earth orbit the plasma environment becomes a conductor, and leakage current and breakdown current are limited by the rate at which charged particles are collected from the plasma. Tests of cable operation in a plasma environ-

ment showed that breakdown voltage was greater than 10 kV. In order to simulate the penetration damage of micrometeorite strikes, the cable was operated with holes and imperfections in the insulation. Leakage current from the plasma then depends on plasma density and the operation voltage but is usually a small loss, occurring without a catastrophic breakdown.

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*Woven ceramic power cables*

## Testing of Advanced Solar Concentrator

The Solar Concentrator Advanced Development (SCAD) Program, begun in September 1985, has successfully developed and demonstrated key solar concentrator technologies required for Space Station *Freedom* applications. The work was performed by the Harris Corporation under contract to NASA Lewis.

The SCAD program was broken into three major tasks. Task I (conceptual design and tradeoff studies) and task II (detailed design) resulted in an offset parabolic concentrator consisting of 19 hexagonal panels mapped to a spherical surface. Twenty-four triangular reflective facets in each hexagonal panel individually focus energy into a heat receiver with an optimum solar flux distribution. The panels are connected by self-locking ball-and-socket latches that provide zero translation displacement in three axes.

Task III included full-scale fabrication and subsequent testing of the SCAD concentrator. Fabrication of 19 hexagonal panels and 48 reflective facets was completed in October 1988. Structural and optical repeatability testing conducted in the NASA Lewis Power System Facility was completed in May 1989. For these tests the concentrator was counterbalanced to virtually eliminate the effects of gravity. Once fully assembled and counterbalanced, the concentrator was tilted into the canted laser scan position. Three support towers provided a fixed reference frame for the repeatability tests. A theodolite measurement system was used to measure and define the three-dimensional positions of 60 sighting targets (three per panel and one at each

support point). A laser scanning system was then used to optically align each of the 48 randomly located facets by centering the reflected laser beam on an opaque target representing the receiver aperture opening. The concentrator was then disassembled, reassembled, and remeasured with the theodolite and laser systems. Theodolite data indicated that the average deviation of the panel normal vector was 0.12 mrad for the 19 panels. Laser beam return data indicated that the average facet alignment deviation was 0.16 mrad. Both measurement techniques resulted in data well within the budgeted panel alignment error of 1.25 mrad.

The SCAD program has provided valuable experience to NASA Lewis and *Freedom* contractor personnel. Detailed designs, modeling tools, fabrication techniques, concentrator assembly procedures, and testing

methods generated in the program have all been baselined in the Solar Dynamic Concentrator Flight Program. The structural repeatability test results have provided confidence in consistent concentrator performance after ground alignment, disassembly, packaging, launch, and reassembly in space.

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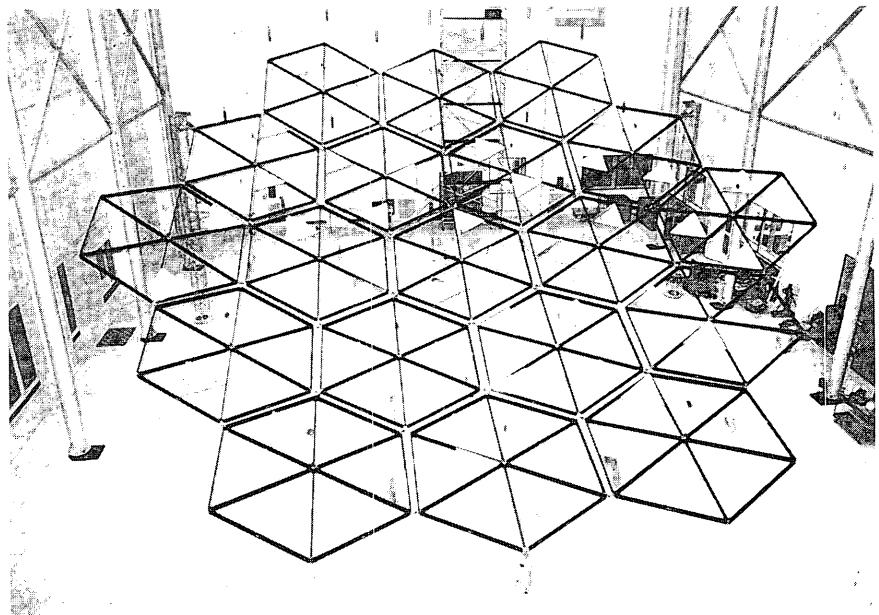
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Corrigan, R.D.; Peterson, T.T.; and Ehresman, D.T.: Update of the SCAD Project. Proceedings 24th IECEC, Aug. 1989.

Solar Concentrator Advanced Development Program: Task I Final Report. NASA CR-179489, 1986.

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SCAD concentrator test configuration

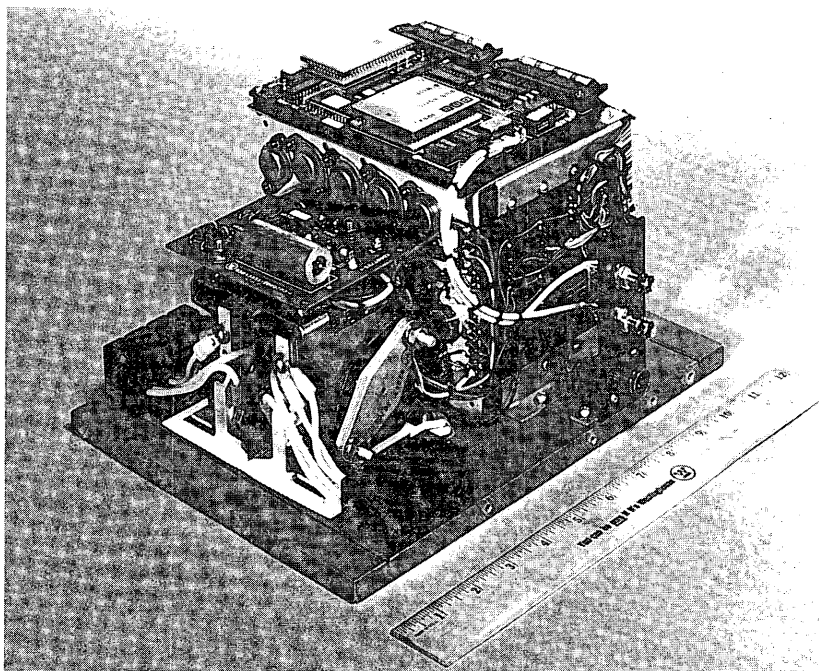
### **Direct-Current Remote Bus Isolator**

The direct-current remote bus isolator is a solid-state power switch used to isolate portions of a dc distribution system. It is intended for use with the power management and distribution testbed to control dc power in the source and load distribution systems. It is capable of current limiting in both directions under overload or faulted conditions to a preset value between 15 and 150 A at an operating voltage of 200 V. The direct-current remote bus isolator can be remotely programmed by an external controller through a dual 1553B data interface. It is functionally similar to the units expected to be used on Space Station *Freedom*. The isolator will be tested in the space station PMAD testbed located in the Power Systems Facility.

The direct-current remote bus isolator was developed for NASA Lewis by the Westinghouse Electrical Systems Division.

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*Direct-current remote bus isolator*

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# Power Generation

## Insolation on Martian Surface

Missions to the Martian surface and activities there will require electric power. Of the several possibilities, photovoltaics can offer many advantages, including a high power to weight ratio, modularity, and a long history of successful application in space—if the solar energy incident on the Martian surface is sufficiently intense. Mars is not only farther from the Sun than Earth but is also known to have occasional intense dust storms. As a result, based on an interpretation of Viking Lander data, which considered only the direct-beam component of the insolation, there has been some skepticism about the potential of photovoltaics for application on Mars.

NASA Lewis is attempting to quantify the insolation, including the effects of dust storms, at the surface of Mars so that planners of Mars missions can accurately determine if photovoltaics is a viable power option. Hourly, diurnal, and daily variations of the global, direct-beam, and diffuse insolation on a horizontal surface were calculated from data measured by the Viking Landers (VL1 and VL2) for the sites visited. The global insolation was derived from the normalized net solar flux function; the direct-beam component was determined by using Beer's law, which relates the insolation to the optical depth of the atmosphere; and the diffuse component was obtained from the difference between the global and direct-beam insolations.

The analysis shows that there is sufficient insolation, primarily from a large diffuse component, to usefully operate a photovoltaic system during both local and global dust storms.

During the spring and summer the insolation on a horizontal Martian surface at the two Viking Lander locations is relatively high because of the low optical depth of the Martian atmosphere. During autumn and winter, when dust storms typically take place, the insolation is lower.

This Mars surface insolation model is being used in Martian mission studies. For example, AeroVironment, Inc., designer and builder of the SunRaycer solar-powered car, has used this model to estimate the output of a flat-plate solar array for a solar-powered Mars vehicle.

This work, which has established the feasibility of using solar power on the surface of Mars, is expected to substantially affect the results of

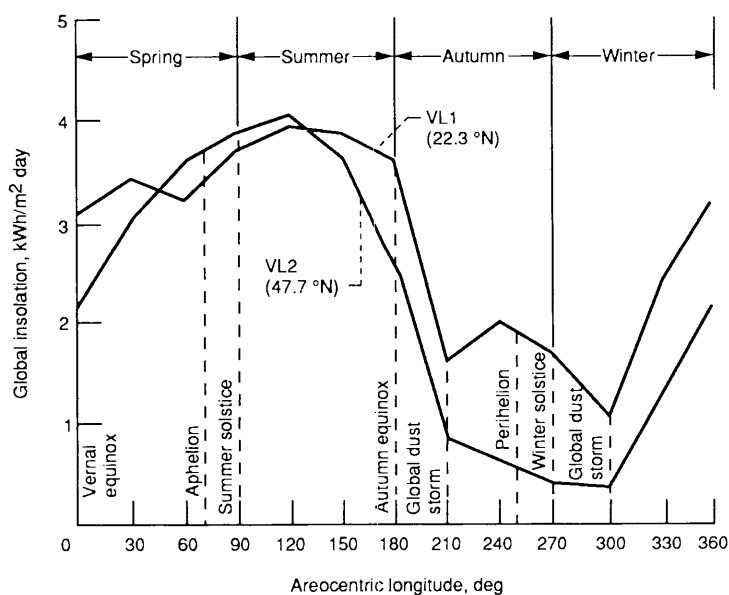
Martian missions. The model will enable more accurate engineering studies and estimates of solar array size and performance than has heretofore been possible.

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*Daily global insolation on a horizontal Martian surface*

## Indium Phosphide Solar Cell on Alternative Semiconductor Substrate

Indium phosphide (InP) solar cells are significantly more radiation resistant than either silicon or gallium arsenide, the cells currently used in space. In addition, air-mass-zero efficiencies of 18.8 percent were achieved with these cells under a NASA Lewis-sponsored contract. Theory predicts that efficiencies of over 21 percent are realistically achievable. However, a major obstacle to the use of InP solar cells in space is the high cost of the InP wafers on which the cells are processed. One solution to this problem lies in depositing a thin layer of InP on a cheaper, sturdier substrate such as silicon. This will result in a substantial saving in both cost and material. For example, the cost of a silicon wafer is about one-fiftieth that of a comparable InP wafer. In addition, the silicon substrate, being mechanically stronger, can be thinner, resulting in reduced weight. For these reasons NASA Lewis has begun a program of research at the Spire Corporation aimed at producing InP solar cells grown on silicon substrates. The feasibility of this approach has been demonstrated under a recently completed 6-month Small Business Innovative Research (SBIR) phase I contract.

Since single crystals are needed for high cell efficiency, the indium phosphide is epitaxially deposited by organo-metallic chemical vapor deposition (OMCVD). The major problem to be overcome is the large number of dislocations due to lattice and thermal expansion misfit. The misfit dislocations are highly undesirable because they drastically reduce cell efficiency. For example, the initial cell processed by Spire, using

InP directly grown by OMCVD on silicon, yielded an efficiency of only 2 percent.

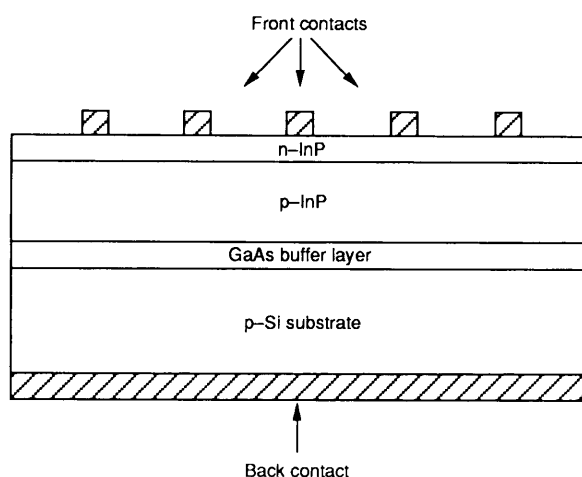
In order to reduce the dislocation density, an extremely thin layer must be placed between the InP and the silicon. The feasibility of this approach was demonstrated by interposing a layer of gallium arsenide (GaAs) between the InP and the silicon; the resultant cell yielded an efficiency of 7.2 percent.

Since there were still misfits between the InP and the GaAs, the demonstration cell was processed simply to prove the feasibility of the layered approach. The solution to the misfit problem is to build up a number of intermediate semiconducting layers on the silicon such that the final layer has little or no misfit with InP. This research is being done under a two-year, SBIR phase II contract with the Spire

Corporation. If successful, this program will result in a cheaper, stronger, lightweight, highly radiation-resistant solar cell.

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**Headquarters program office:** OAST



*Schematic of layered indium phosphide solar cell*

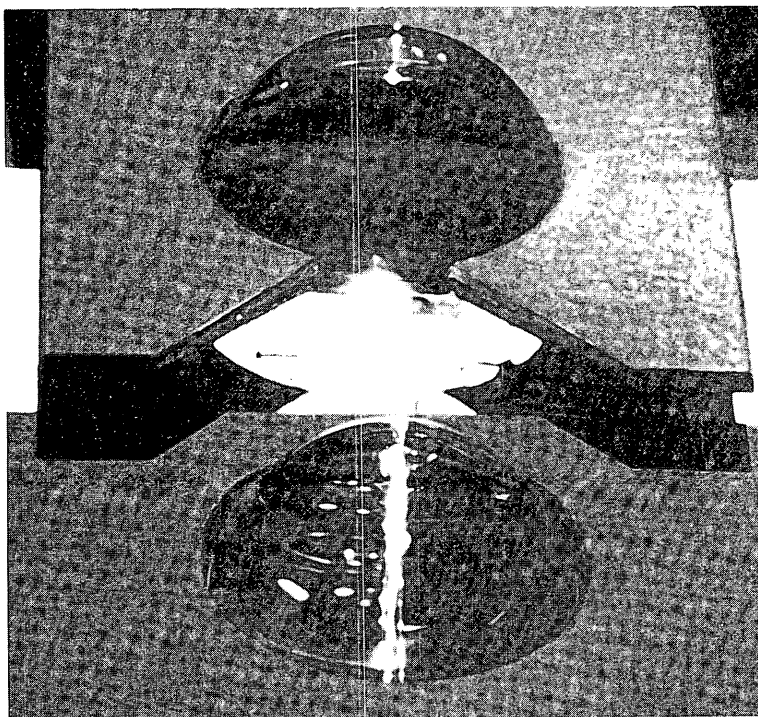
## Mini-Dome Fresnel Lens for Advanced Photovoltaic Concentrator Arrays

Photovoltaic concentrator arrays for space power systems offer the advantage of operating smaller photovoltaic devices at higher efficiencies.

However, losses encountered in collecting and concentrating the sunlight can diminish the gains of higher operating cell efficiency and make increases in system performance marginal. Studies have shown that the mini-dome Fresnel lens concentrator can significantly increase efficiency and reduce weight relative to current space-qualified concentrator optics.

The mini-dome Fresnel lens concentrator is a point-focus refractive lens that was developed under a Small Business Innovative Research (SBIR) contract by Entech, Inc. The concept is the first attempt to use dome-shaped refractive optics in a space power system and is an outgrowth of Entech's experience in terrestrial photovoltaic systems. The patented lens has a smooth outer surface with individually tailored Fresnel facets along the inside of the domed surface. The combination of the domed shape and the Fresnel facets provides a unique geometry that minimizes reflection from each Fresnel prism, thereby providing maximal sunlight transmittance through the lens. Each lens provides a concentration of 100 suns to a high-efficiency photovoltaic concentrator cell at a focal length of 4.0 cm. In order to increase the packing factor of these devices within an array, each lens is cut to a 3.7-cm by 3.7-cm square aperture. Analytical studies have predicted over 95-percent optical efficiency for a lens with an antireflection coating.

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*Prototype of mini-dome Fresnel lens with cutaway view showing light focused on photovoltaic cell*

During 1989 a prototype mini-dome Fresnel lens was manufactured and tested. In these first tests a net optical efficiency of 86 percent was measured. Further refinements in the lens manufacturing process should yield a production lens capable of a 92-percent optical efficiency. In conjunction with this emphasis on lens efficiency, work is also continuing to ensure survivability of the lens materials within the space environment.

The mini-dome Fresnel lens, in combination with other developments such as the prismatic cell cover and high-efficiency gallium arsenide concentrator cells, will be used to construct an array that would mini-

mize both area and weight requirements for future space power systems. The development of a high-performance concentrator system would also provide the array structure required for utilizing a new generation of high-efficiency solar cells.

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## Advanced Stirling Space Engines

In August 1988 a contract was awarded to Mechanical Technology Inc. (MTI) for the fabrication of an advanced free-piston, 25-kW Stirling space engine. A full-scale experimental engine is to be demonstrated by the end of 1992. The engine will operate at 1050 K and serve as a low-temperature preprototype of a 1300 K engine.

A component test engine is being designed and will be fabricated to address the many component development needs of the space engine. Since the space engine will be designed to reject heat at 525 K, the entire lower end of the engine, including the alternator, will operate at or near 525 K. A major design concern is the maintenance of proper clearances between the piston and the cylinder as the lower-end temperature is varied between ambient and

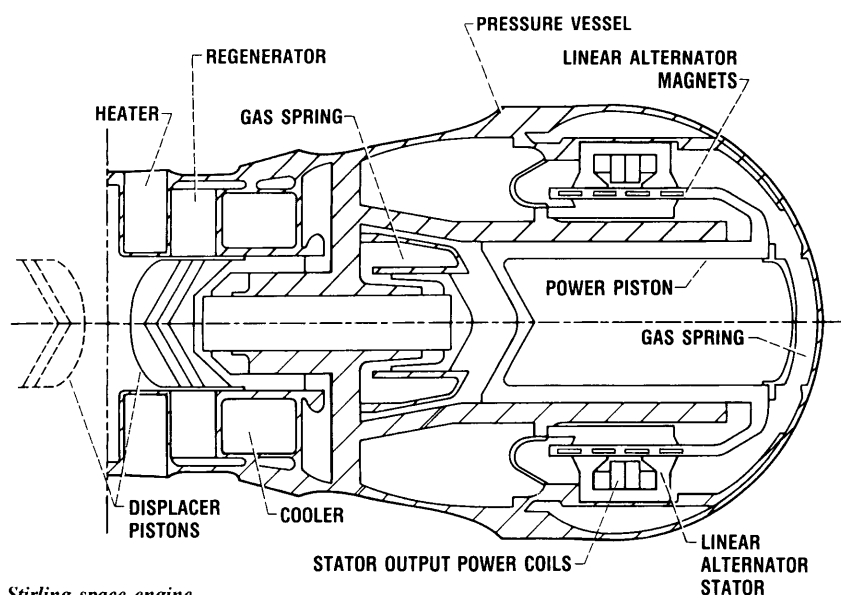
525 K. The lower end of the test engine, coupled to the hot end of an existing engine (the space power research engine), will be tested so that the lower-end design concerns can be addressed early. Other areas of concern are the effect of temperature on the samarium-cobalt alternator magnets and on alternator electrical insulation. Two additional technology areas currently being addressed are heat exchangers and gas bearings.

Several heater concepts were evaluated for the Stirling space engine, and an innovative heater was chosen that does not require welding or brazing to create the heat exchange surfaces. The heater is fabricated by electrical discharge machining all gas passages and heat pipe surfaces. The result is a heat exchanger equivalent to a 2000-tube tube-in-shell

heat exchanger that would normally require 4000 braze joints.

Both hydrostatic and hydrodynamic gas bearing systems will be tested. Preliminary component-test-engine design analyses have shown that both bearing systems, when properly integrated into the engine, have about the same effect on engine performance. A failure mode and effect analysis to compare the potential reliability of the two systems is being performed.

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*Stirling space engine*

## Advanced Stirling Engine Conversion System

The Stirling engine has been identified by the U.S. Department of Energy (DOE) and Sandia National Laboratory Albuquerque (SNLA) as the most promising heat engine for conversion of solar energy to electric power. Studies have shown that the Stirling conversion system has the potential to meet the DOE long-term goals. The free-piston Stirling engine has been chosen because of its potential for high cycle efficiency, long life with high reliability, and low production costs. NASA Lewis manages the Advanced Stirling Conversion System (ASCS) Program for DOE/SNLA.

Two conceptual design studies, completed in 1987, featured the free-piston Stirling engine integrated with a liquid-metal receiver operating at 700 °C. The design phase of the

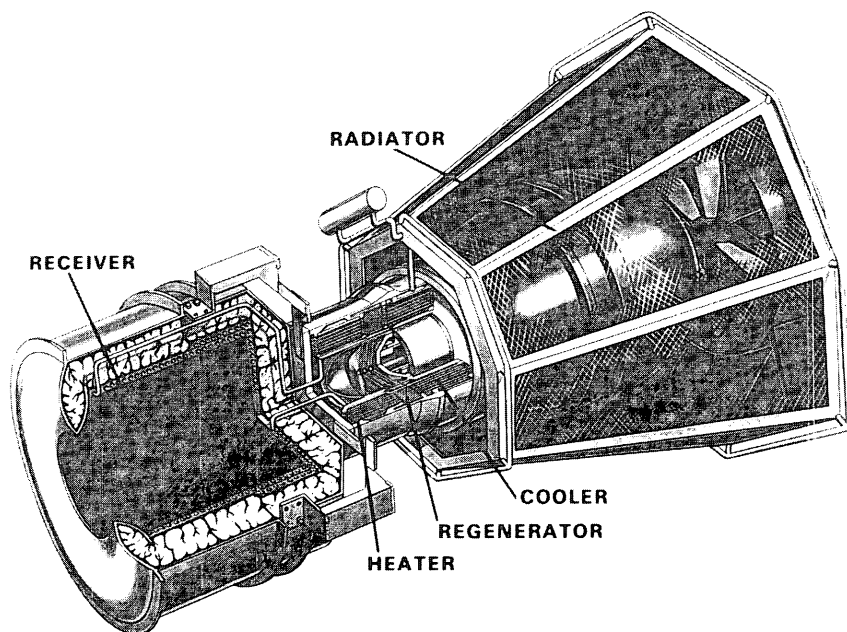
ASCS continues with two industry teams, Cummins Engine Company (CEC) and Stirling Technology Company (STC). CEC's design uses a free-piston Stirling engine with a linear alternator; STC's design uses a free-piston Stirling engine with hydraulic output coupled to a rotary alternator. Both designs can operate as stand-alone units and provide nominally 25 kW of electric power to a utility grid while operating on solar energy from an 11-m-diameter parabolic dish concentrator. Independent studies have shown that both designs are manufacturable and can meet the DOE long-term cost goals if produced in quantities of 10,000 per year. This effort also involves manufacturers during the design phase to enhance free-piston Stirling technology and subsequent commercialization of the ASCS. Current plans

call for the completion of the design, fabrication, and testing of an advanced Stirling conversion system in 1990. Delivery of a complete system to the SNLA test facility in New Mexico is expected in late 1991.

Ground testing of the ASCS will provide NASA an opportunity to evaluate the free-piston Stirling engine as a solar dynamic system for space. Additional advanced Stirling conversion systems operating on utility grids will be evaluated in order to identify reliability and life issues.

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Funding source: DOE



*Conceptualized free-piston Stirling engine*

## Free-Piston Stirling Engine With Sodium Heat Pipe

A conceptual design of the Stirling space engine has been generated as part of the Civil Space Technology Initiative (CSTI) Advanced Technology Program. A major goal of the design was to reduce the number of critical joints. One concept proposed using 40 modular heat exchangers with integral heat pipes to transport heat from the heat source to the engine.

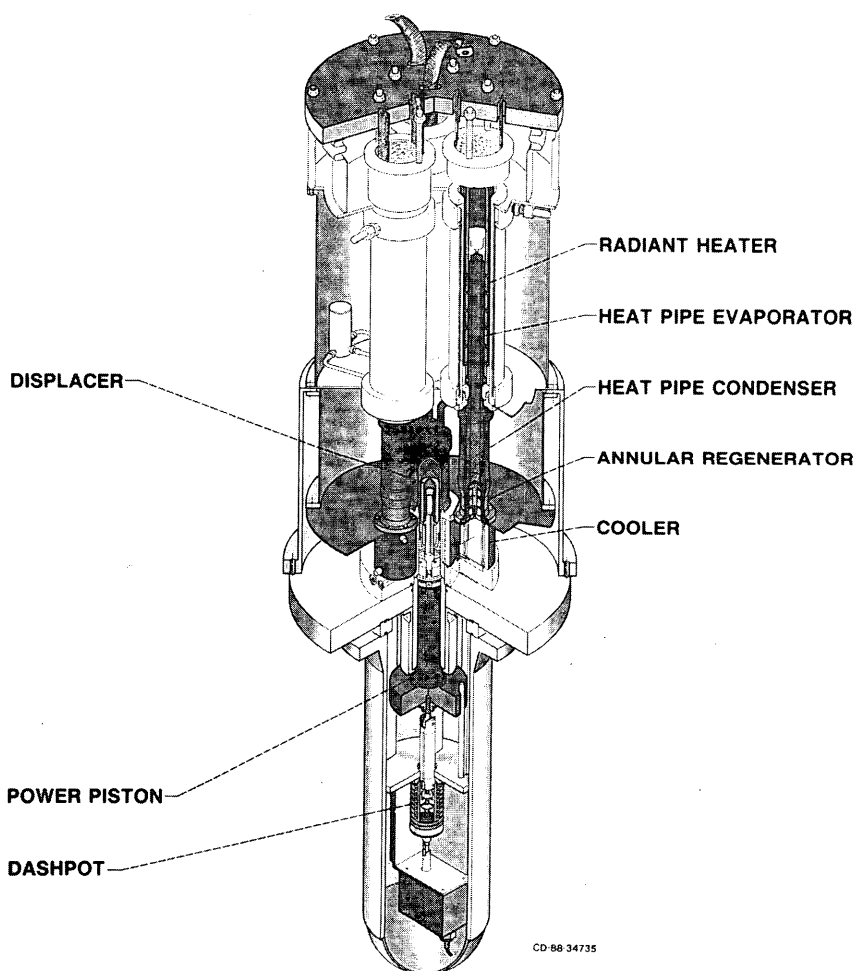
A demonstration of the modular concept was undertaken before committing to the detailed design of the heat exchangers. An existing free-piston Stirling engine was modified as a testbed for modular heat exchanger evaluation. The engine incorporated three heat exchanger modules, each having an integral sodium-filled heat pipe. The thermal loading of each module simulated the conditions projected for the Stirling space engine modules. Initial tests were performed with the heat pipes operating against gravity. The entire engine will be inverted and tests will be run with the heat pipes operating in a gravity-assisted mode. The variation in engine performance with heat pipe orientation will quantify the effect of excess heat pipe working fluid on heat exchanger performance.

Initial evaluation of the heat exchanger modules has shown the modular concept to operate successfully on a free-piston Stirling engine. These test runs have been performed with the heat pipes operating in parallel against gravity. Tests have been run with the heat pipe temperature as high as 1050 K. Detailed temperature profiles have been measured in the gas and the metal to

aid in understanding the thermal loading characteristics inherent in Stirling engine heat exchangers.

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*Sodium-heat-pipe heat transport system*

# Energy Storage

## Thermal Energy Storage Technology Experiment

NASA Lewis is developing a power system for future applications in space. A goal of one advanced development program is to make the promising solar dynamic power system a more viable candidate for in-space applications. The biggest and heaviest part of the solar dynamic power system is the heat receiver. Its function is to provide a nearly constant working fluid temperature ( $\sim 1120$  K) for the system as it cycles through sunlight and shade while in low Earth orbit. A lighter weight and higher efficiency heat receiver is possible if a thermal energy storage material that changes phase is used (i.e., LiF). Lithium fluoride provides high heat-of-fusion energy at nearly a constant temper-

ature during its phase change. The periodic phase change in low Earth orbit is accompanied by void formation in the material. The characterization of void formation for thermal energy storage materials in microgravity is critically needed. It will help ensure that future advanced heat receiver designs will perform reliably and efficiently in a microgravity environment.

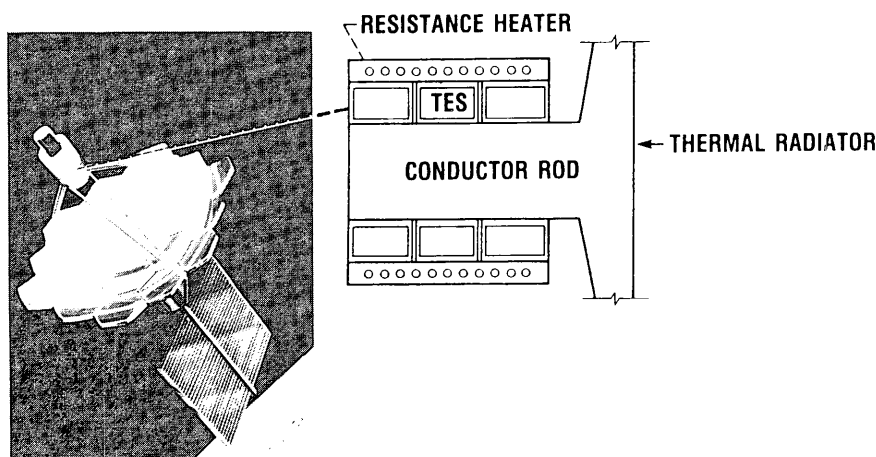
A thermal energy storage technology (TEST) flight experiment is now in the engineering development phase. A hardware geometry containing LiF will be designed, developed, and tested to provide microgravity test data. From the test data, void formation will be characterized and

performance impacts on advanced heat receiver design predicted. An in-house project team of Lewis and support service contractor (Sverdrup Technology, Inc.) personnel manages and implements this flight experiment. The TEST flight experiment will fly as a complete system in a Getaway-Special configuration. The first flight hardware contains LiF in an annular cylinder with heaters wrapped around it. A conductive rod in the cylinder will be periodically exposed to the low temperature of space in order to provide the cooldown needed for the LiF to change phase. Planning for this test configuration includes a minimum of four heat and cool cycles in the microgravity environment.

Temperature variation with time, along with void size and location, will be compared with the predictions of the NASA/Oak Ridge Void Experiment (NORVEX) computer program that is under development. This program will perform three-dimensional analyses of heat transfer, energy storage, fluid movement, and void location under microgravity conditions.

Results from the TEST flight experiment are expected to provide the needed validation of the NORVEX program. A validated program helps ensure that future designs of advanced solar dynamic heat receivers will have high thermal efficiency, reliable performance, and low mass per unit of power generated.

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*Thermal energy storage technology experiment*

## Sodium-Sulfur Battery Flight Experiment

Future NASA and Department of Defense missions will require batteries capable of storing and delivering higher power at high rates. Sodium-sulfur batteries have been under development for over 20 years for use in electric vehicles and as load-leveling storage for electric utilities. Only recently have they been considered for space applications. They offer two or three times the power of the presently used nickel-hydrogen batteries. In fact, the sodium-sulfur system is the most advanced of the high-specific-energy batteries.

Sodium-sulfur cells, which operate at 300 to 400 °C, use molten sodium and sulfur electrodes and a solid  $\beta$ "-alumina electrolyte. The sulfur electrode material is actually a mixture of sulfur and sodium polysulfide, the composition varying according to the state of charge. The sulfur electrode is supported in a graphite felt matrix. The graphite matrix provides both conductivity and wicking functions for mass transport to and from the electrolyte. The  $\beta$ "-alumina transports sodium ions between the sodium electrode and the sulfur electrode.

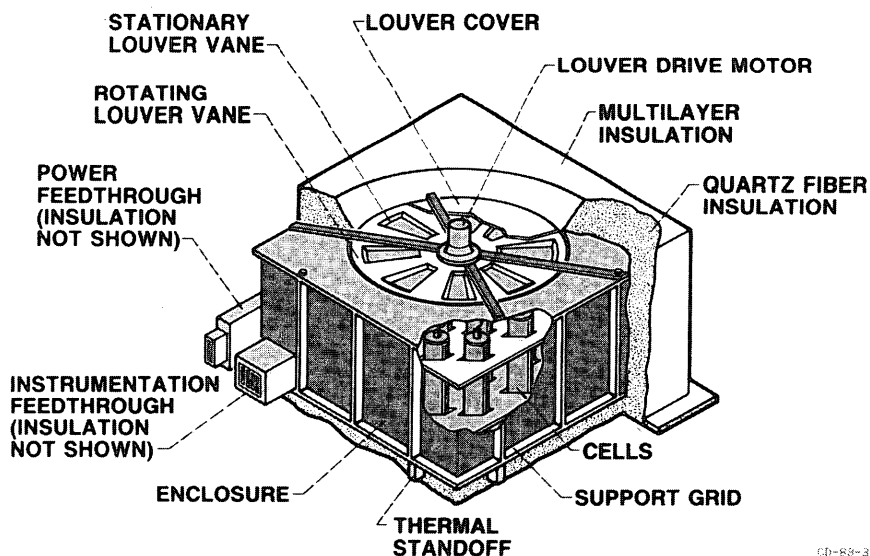
Sodium-sulfur cells represent a departure from typical electrochemical storage devices in that the electrodes are liquid rather than solid and the electrolyte is solid rather than liquid. This presents concerns about the operation of such a system in microgravity environments. Of primary concern is the transport of sodium to the separator, where it is converted to sodium ions, and the transport of sulfur or polysulfides to the separator, where the sodium ions are removed. This

phenomenon is further exasperated by the fact that the volume of sodium and sulfur or polysulfide depends upon the state of charge.

NASA has entered into a contract with Ford Aerospace and Communications Corporation to design a microgravity experiment that would demonstrate the wicking functions for transport of electrode materials to the electrolyte interface under actual microgravity conditions.

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Baseline sodium-sulfur battery configuration

CD-88-3

## High-Specific-Energy IPV Nickel-Hydrogen Cell

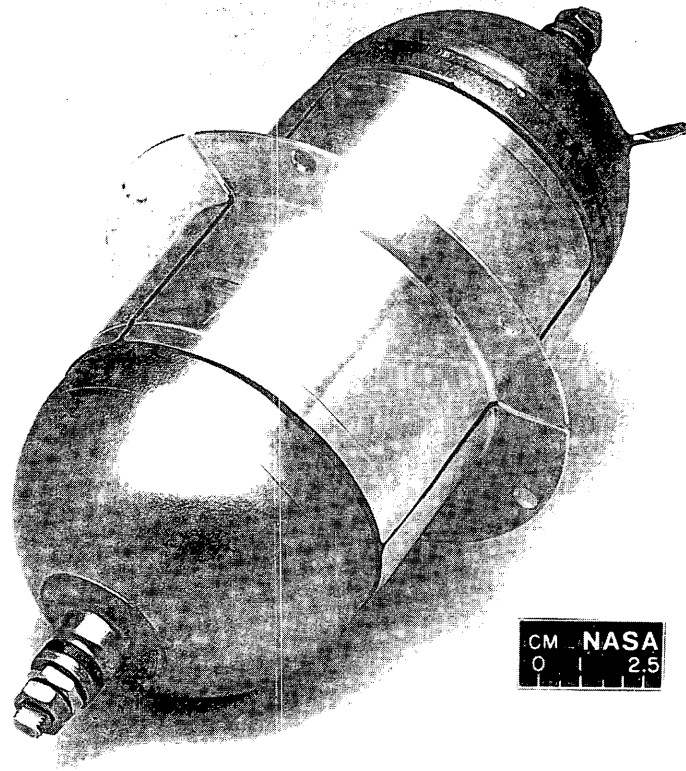
As part of an overall program to advance the technology of nickel-hydrogen battery cells for use in energy storage systems for space power, an advanced individual-pressure-vessel (IPV) nickel-hydrogen cell was designed with a specific energy of 100 Wh/kg (the state of the art is 50 Wh/kg). This is significant because as the power required for satellites increases, the fraction of satellite mass occupied by the power system also increases; reducing payload mass. This situation can be altered by increasing the battery specific energy. Also for a fixed power requirement, increasing the specific energy will allow an increase in payload, which translates into higher profits for a commercial satellite.

The cell specific energy was increased primarily in the following ways: A 90-percent-porous fibrous plaque was used for the nickel electrode rather than the state-of-the-art 80-percent-porous, sintered dry powder plaque. The plaque loading level was increased from 1.65- to 2.0-g/cm<sup>3</sup> void volume, and the thickness of the nickel electrode was increased from 30 mils to 80 mils, which reduced the cell component count.

Flight cells will be fabricated and performance tested to demonstrate this advanced design.

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*ipv nickel-hydrogen cell*

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## Cryogenic Reactant Storage for Lunar-Base Regenerative Fuel Cells

Although photovoltaic power systems have provided reliable power for most U.S. space missions, these systems are usually confined to planetary orbit domains. As the U.S. space program moves into the 21st century, photovoltaic systems will be used for planetary surface missions as well. A primary candidate for the energy storage subsystem for lunar surface applications is the hydrogen-oxygen regenerative fuel cell. This system exhibits the highest energy density of all nonnuclear systems for storage periods exceeding 2 hours.

Conventional hydrogen-oxygen regenerative fuel cells (RFC's) store the reactants as gases in pressurized tanks. For low-Earth-orbit applications, tankage accounts for a small percentage of the total power system mass. However, as the storage time increases, an increasing percentage of the RFC subsystem mass lies in tankage. For lunar missions, where the storage time requirements approach 350 hours, tankage makes up the overwhelming majority of the system mass. Because tankage does not directly contribute to the power and energy output of the system, any mass reduction would be advantageous. This is especially significant in view of the cost of delivering payload to the lunar surface.

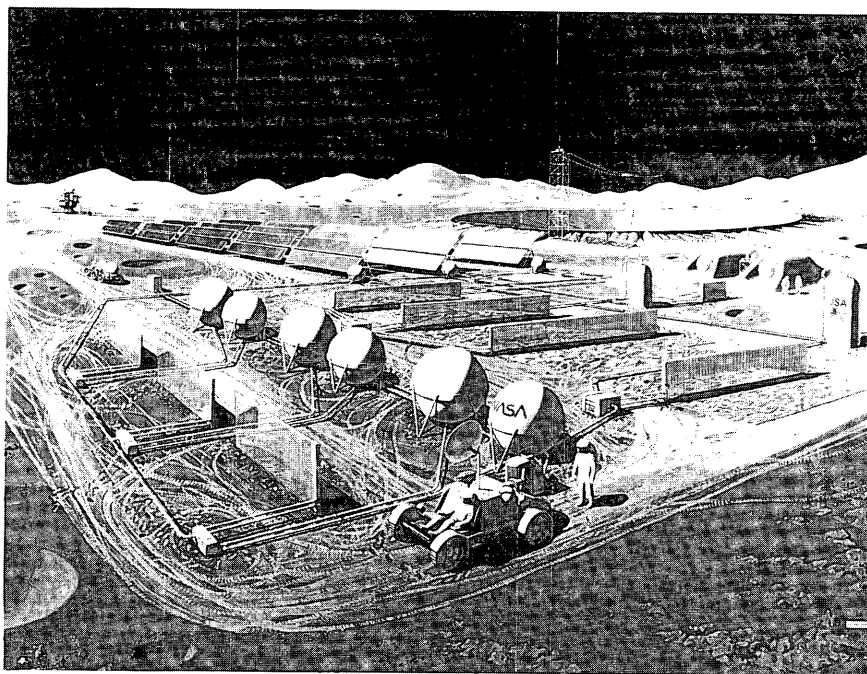
One option for reducing tankage mass is to liquefy the reactants and store them as cryogens rather than as pressurized gases. A conceptual system study was carried out at NASA Lewis to determine the mass impact of integrating a cryogenic reactant storage system with a hydrogen-oxygen RFC to provide on-site electric power during the lunar

night. The system consists of a fuel cell unit, an electrolysis unit, a gaseous hydrogen-oxygen drying subsystem, a hydrogen-oxygen liquefaction subsystem, and reactant tankage. A gallium arsenide sun-tracking array provides power to the electrolysis unit and the drying and liquefaction subsystems. Vertically oriented heat pipe radiator panels are used for thermal management.

Power levels of 20 and 250 kW were considered. The resulting overall mass reduction was determined to be approximately 50 percent relative to RFC systems with gas storage. With an approximate 5:1 propellant-to-payload mass ratio to

deliver a payload to the lunar surface, the power system mass savings translates into a considerable propellant mass savings as well. The total lower mass results in fewer launches required for delivery, and therefore a significant reduction in launch costs. The system also offers synergistic benefits to on-site users, such as availability of primary fuel cell reactants for surface rover vehicles and cryogenic propellants for orbit transfer vehicles.

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*Artist's concept of lunar-base regenerative fuel cells*

## Development of Thermal Energy Storage Code

Solar dynamic systems operating with input energy rates that differ from power generation requirements must incorporate an energy storage system. Advanced solar dynamic systems use the heat of fusion of high-temperature salts to store energy during sunlight periods for use during shade periods.

One concern in thermal energy storage (TES) designs is the lack of a comprehensive analysis predicting the behavior of TES materials. This lack is particularly significant in advanced solar dynamic systems, where TES materials, typically fluoride salts and their eutectics, undergo large changes in density as they change phase. A void formed in this way can create a "hot spot" in the solar receiver or distort the TES container—either can result in

component failure. A verified analysis for predicting the location and behavior of voids in various container geometries can avert serious consequences.

NASA Lewis has contracted with Oak Ridge National Laboratory to develop such an analytical tool. The program, called NORVEX, has been designed to analyze three-dimensional, cylindrical coordinate configurations for a gravity range from microgravity to 1 g. In order to keep operations within reasonable computer time constraints, the program is divided into seven modules, each operating in an independent heat transfer or fluid mode. A subroutine serves to iterate among the modules.

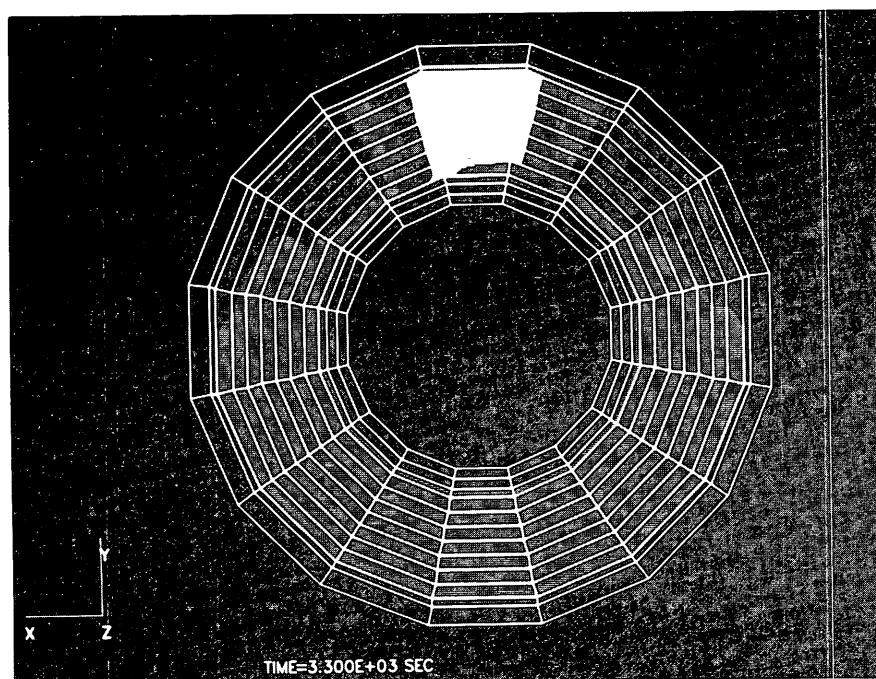
NORVEX will be outputted in several forms—isotherms at desired time

steps, maximum and minimum temperature profiles during a cycle, and a phase map denoting locations of the liquid, solid, and void zones.

The 1-g program has been delivered to Lewis, where it is being adapted to a range of design parameters. Oak Ridge has completed and is validating the microgravity program.

NORVEX will be verified by data from four flight packages, each designed to be flown as self-contained units in the space shuttle. TES materials and their containers selected for the test are typical of current considerations for advanced solar dynamic system applications. The two TES materials chosen are lithium fluoride and a fluoride eutectic; container geometries are annular and wedge shaped. Both wetting and nonwetting conditions will be investigated. The design of the TES container, the conditions of heat flow into and out of the package, and operation under microgravity will be modeled by the code. The temperature data will be compared with the predictions of NORVEX. Code predictions will also be compared with the visual evidence of the shape and location of the voids upon the postflight retrieval of the package.

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*Phase map of thermal energy storage container after 30-min zero-gravity flight*



## Space Station *Freedom* Nickel-Hydrogen Cell Test Program

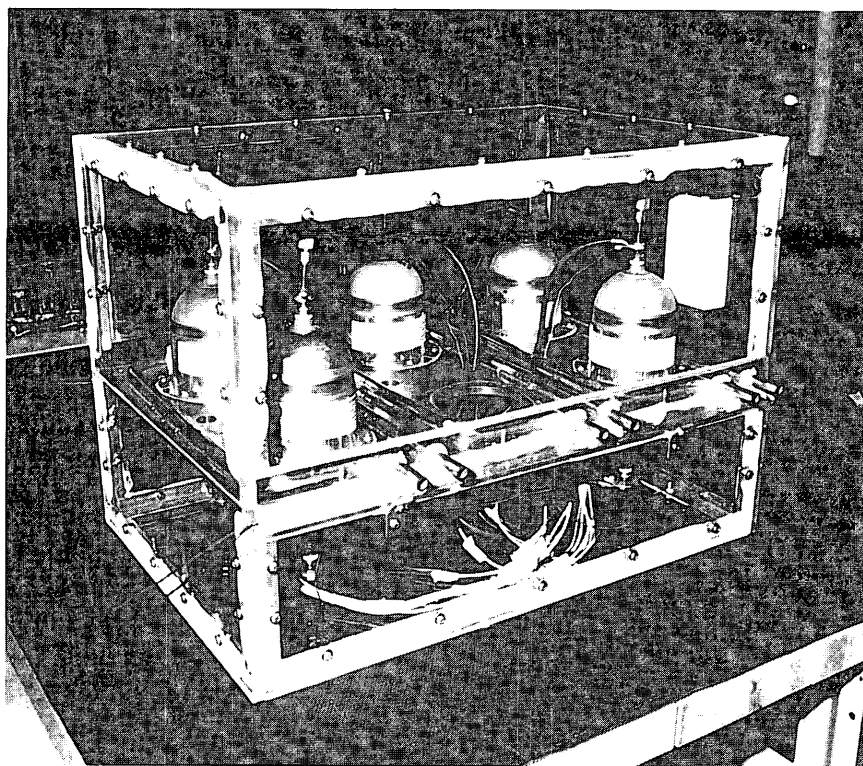
In March 1986, when nickel-hydrogen cells were chosen as the energy storage system for Space Station *Freedom*, the data base on their life and performance characteristics in low Earth orbit was limited. Therefore, NASA Lewis began two test programs, one in house and one at the Naval Weapons Support Center (NWSC) in Crane, Indiana. For the first program a nickel-hydrogen cell laboratory was built at Lewis.

Lewis is screening a large number of cell designs to determine individual cell life and performance characteristics. Cells were purchased, through existing Lewis contracts, from Whittaker-Yardney Power Systems, Eagle-Picher Industries, and Hughes Aircraft Company. The resulting 40-cell test matrix consists of 13 different cell designs including both 50- and 65-Ah-capacity cells. Currently, 22 cells are on life test at 35-percent depth of discharge, with the first cells having accumulated 6 months of life data. The other cells are undergoing acceptance and characterization testing.

The Naval Weapons Support Center is characterizing and endurance (life) testing a statistically significant number of nickel-hydrogen cells to verify the Space Station *Freedom* requirement of five-year life at 35-percent depth of discharge. The test matrix consists of 130 nickel-hydrogen cells from each of three vendors: Whittaker-Yardney, Eagle-Picher, and Gates Aerospace Batteries. Each vendor will supply 50 "standard" 65-Ah cells that represent a low-risk, state-of-the-art, low-Earth-orbit design. They will also supply 20 "advanced" 65-Ah

cells and 60 "advanced" 81-Ah cells. For the advanced design the vendors were directed to include at least two recent technology developments to improve cycle life and electrical performance. The choice was left to the discretion of the vendor. The cells will be series connected and life tested in 10-cell packs. Storage tests will be conducted at various conditions to determine the method that will minimize capacity loss. The first cells arrived in October 1989.

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*Five-cell nickel-hydrogen battery pack being prepared for testing*

# Thermal Management

## Heat Dissipation by a Converging-Liquid-Drop Radiator

The liquid-drop radiator has been under investigation as a potentially lightweight and easily deployable device for radiating away large amounts of waste heat arising from space power systems. A design having converging streams of liquid drops would facilitate collection of the drops after they have cooled by direct exposure to outer space.

An analysis was carried out at NASA Lewis to examine the radiating characteristics of a converging droplet layer. The convergence decreases the outer surface area available for energy dissipation and also changes the local radiating characteristics of the layer by increasing the number density of the drops as distance increases in the flow direction. The analysis included the effect of scattering and partial reabsorption of the emitted energy within the drop-filled region. The solution required numerical integration of the equations governing radiative transfer along the length of the radiator. Solutions were carried out for various optical thicknesses of the layer at the start of the converging region. A simplified solution using a locally uniform temperature distribution across the layer was found to provide a good approximation for some ranges of parameters. Performance curves were obtained that showed the radiator temperature variation for various amounts of radiator convergence.

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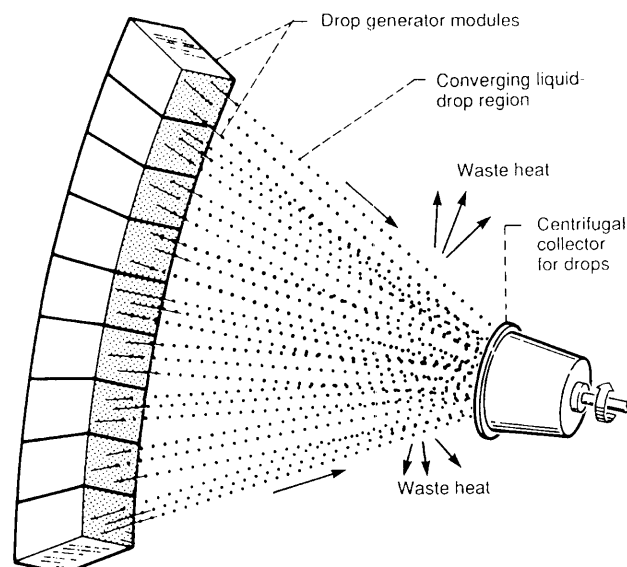
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White, K.A., III: Liquid Droplet Radiator Development Status. AIAA Paper 87-1537, July 1987. (Also NASA TM-89852.)

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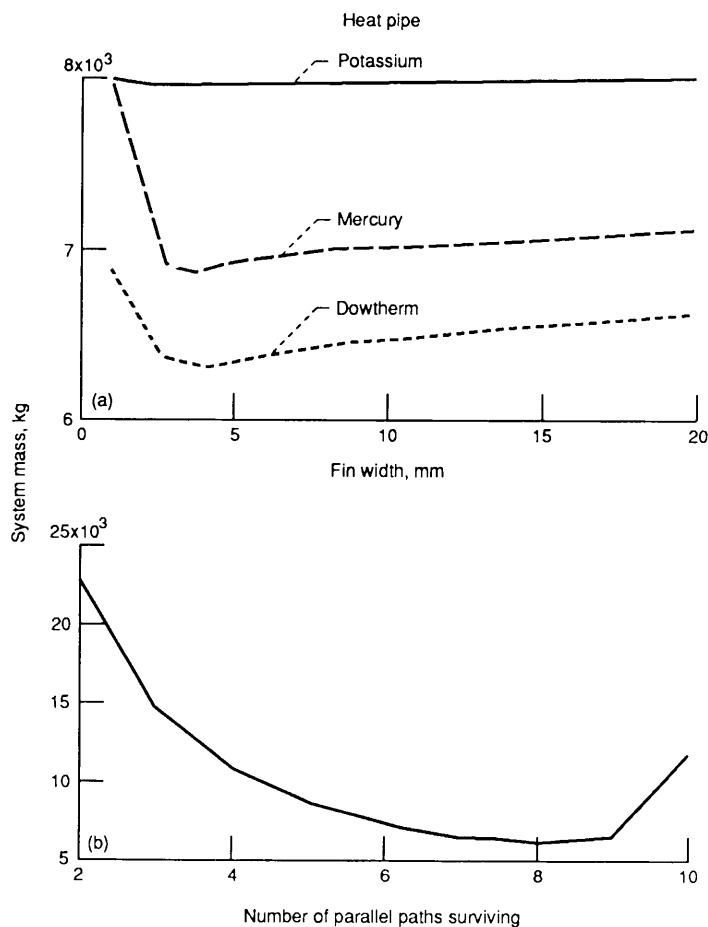


*Liquid-drop radiator*

### Design and Analysis Code for Combined Pumped-Loop, Heat Pipe Radiator

Current heat rejection systems for spacecraft are made primarily of heat pipes and pumped loops. Although a heat pipe system often has a lower mass than a comparable pumped-loop system, it is often impossible to configure systems to use heat pipes alone. Therefore, it may be necessary to combine these two heat transfer systems to successfully and economically remove heat from a spacecraft. To this end, NASA Lewis has developed a steady-state computer code that is capable of designing and analyzing combined pumped-loop and heat pipe radiators.

The code's capabilities and design allow it to be used for a wide variety of applications to meet varied system needs. A large temperature drop in the radiator, typical of a Brayton power conversion system, which may require the use of several different types of heat pipes, can be accommodated by the code. The program is capable of performing basic design and analysis of a radiator system as well as a mass-minimizing optimization analysis. Several parameters pertaining to the heat pipes can be optimized with the code, including the width and length of the radiating fin (attached to the heat pipe) as well as the diameter of the heat pipe. Additionally, parameters affecting overall system design, such as system heat pipe redundancy, may be chosen as one step in the radiator design optimization process.



Effect on total radiator mass: (a) of varying pin width, (b) of varying number of parallel paths

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## Liquid-Sheet Radiator

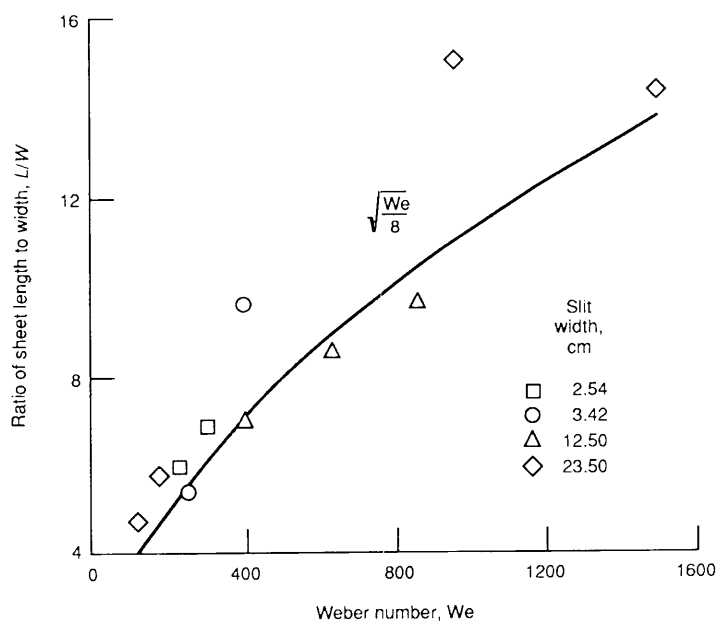
Using a flowing, thin sheet as the radiating surface results in a low-mass space radiator immune to micrometeoroid damage. A unique characteristic of thin-sheet fluid flow is that the flow coalesces to a point, resulting in a triangular shaped sheet. Surface tension forces at the edges of the sheet cause cylinders to form that grow in diameter in the flow direction. As the cylinders grow, the sheet narrows to satisfy conversion of mass. The end cylinders eventually meet at a point. This coalescing of the flow to a point is ideal for collecting the flow in a space radiator.

In the past, small sheet flows have been investigated. A new facility allows the study of larger flows (sheet width,  $W \leq 23.5$  cm, sheet length,  $L \leq 3.5$  m). The dependence of length-to-width ratio  $L/W$  on the flow variables is currently being measured. Theoretical analysis for negligible gravitational effect predicts  $L/W = \sqrt{We}/8$ , where  $We = \rho \tau w_o^2 / \sigma$  is the Weber number and  $\rho$  is the fluid density,  $\tau$  is the sheet thickness,  $w_o$  is the flow velocity, and  $\sigma$  is the surface tension. Theoretical  $L/W$  has been compared with experimental data for several sheet flows of Dow-Corning 705 diffusion pump oil. More data for different sheet thicknesses and widths will be taken in the future.

For low-temperature ( $< 400$  K) applications diffusion pump oils such as Dow-Corning 705 are suitable radiator liquids. However, at high temperatures only liquid metals have low enough vapor pressure to operate at vacuum conditions without significant evaporation losses. The emissivity of a Dow-Corning 705 sheet has been calculated from

experimentally measured spectral transmission data. Results of that calculation predict an emissivity greater than 0.8 for sheets thicker than  $100 \mu\text{m}$  in the 300 to 400 K temperature range. These emissivities are suitable for radiators in space.

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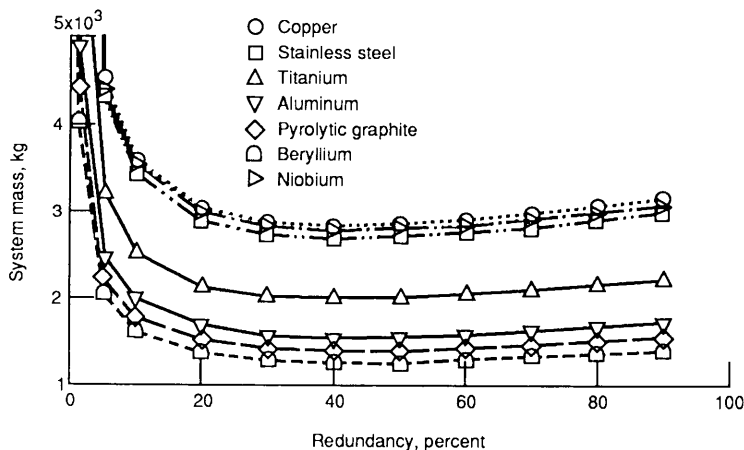
Sheet flow length-to-width scaling

## Hypervelocity Impact on Radiator Systems

The presence of micrometeoroids and debris in the orbital space environment causes space power system radiator designs to be significantly different from those for planetary applications. Micrometeoroids travel at speeds that average approximately 20 km/sec; most space debris travels at 7.5 to 15 km/sec. When these particles impact a radiator, significant energy is imparted to the radiator material. A puncture results if the material is not thick enough to withstand that energy. A puncture located in a part of a radiator containing fluid will cause a failure of that section and make it useless for transferring heat.

Several options are available to ensure the survivability of a radiator under various environmental threats. Materials may be made thick enough, called armoring, to be able to withstand the expected impacts by the space debris and micrometeoroids. But this causes a system to become extremely massive. An alternative is to use thin component materials and allow for a certain number of destructive impacts by adding extra components to the system, called redundancy. The correct combination of redundancy and armoring produces a minimum-mass system.

The various materials available for system construction often have significantly different thermal characteristics and armor capabilities. The fewer redundant components, the thicker the materials must be to withstand impacts. However, this lowers the heat transfer capability of the component. Therefore, NASA Lewis has developed techniques for comparing basic radiator system



*Effect of material choice on radiator system mass as a function of component redundancy*

materials. Seven perspective radiator materials were compared by using NASA's thin-plate penetration model. A redundancy of 20 to 30 percent provided a minimum system mass.

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## Thermal Analysis of Multiphase Fluids

Detailed understanding of heat transfer and fluid flow is required for many aerospace systems. These systems often include phase change and operate over a range of accelerations or gravitational fields. Important examples of such systems include thermal energy storage devices, cryogenic fluid management systems, and materials processing experiments. Other systems, such as batteries and thermal management devices, might have to withstand initial or inadvertent freezing in the low temperatures of space.

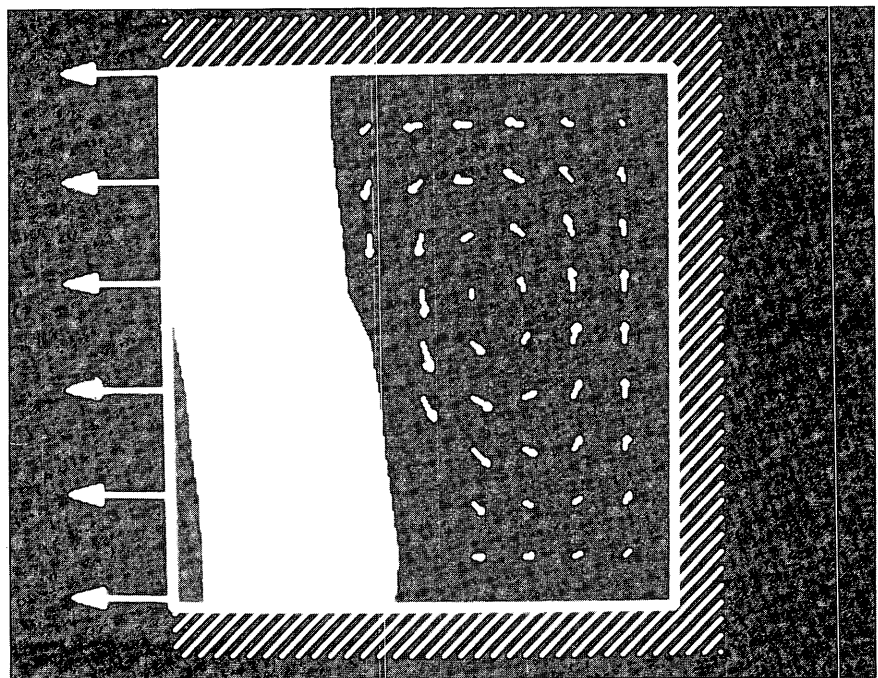
Because of the time required for many phase change problems, most experimental studies are impractical in low-gravity facilities. There are also few analytical tools that can model such systems. Most of these use empirical relations for the heat and mass transfer along with finite difference numerical techniques. Although adequate for simple geometries, they are either inaccurate or difficult to apply when the geometry is complex.

To address this need, a computer program called PHASTRAN was developed. PHASTRAN does not rely on empirical heat and mass transfer relations but instead solves the conservation laws of energy, momentum (Navier-Stokes), and mass, as well as an equation of state. The complete variable-property form of the governing equations is used, instead of the commonly used Boussinesq approximation. This allows for analysis of materials with greatly varying properties, typical of phase change problems. Also, because it is finite element based, it can easily model highly irregular boundary conditions and geometries.

PHASTRAN is a fully implicit transient analysis capable of analyzing systems having combined conduction and convection (free and forced) with or without phase change. Its application is presently restricted to laminar flow and Newtonian fluids in two dimensions. Future enhancements will include three-dimensional capability and non-Newtonian fluids.

PHASTRAN is written in the array-processing language APL2 and has run on 386-based microcomputers as well as an MVS/XA mainframe. If available under MVS/XA, PHASTRAN can take substantial advantage of vector-processing hardware, with no modification to the source code.

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*PHASTRAN-calculated phase distribution, temperature control, and fluid velocities*

## Plasma & Radiation

### SPEAR Plasma Testing

Future space power systems will require megawatts of power. The most efficient means of distributing this power throughout the spacecraft is by using the highest voltage feasible on the bus. This reduces the necessity of large cables carrying kiloamperes of current. If the power system can use the vacuum of space as the insulating medium, weight can be reduced further while increasing reliability and lowering maintenance requirements. Using space as the insulating medium requires that all components of the high-voltage power system be exposed to the space environment.

The Space Experiments Aboard Rockets (SPEAR) Program is an experimental program managed by the Defense Nuclear Agency, with NASA Lewis as a coinvestigator to test the feasibility of using the vacuum of the low-Earth-orbit space environment as the insulating medium. The vacuum in low Earth orbit consists of positively and negatively charged particles in equal numbers with a maximum charge density of approximately  $5 \times 10^6 \text{ e/cm}^3$ . It is known that high-voltage surfaces exposed to a plasma environment could have large coupling currents from the plasma or arc discharges from the high-voltage surfaces that would be detrimental to the spacecraft.

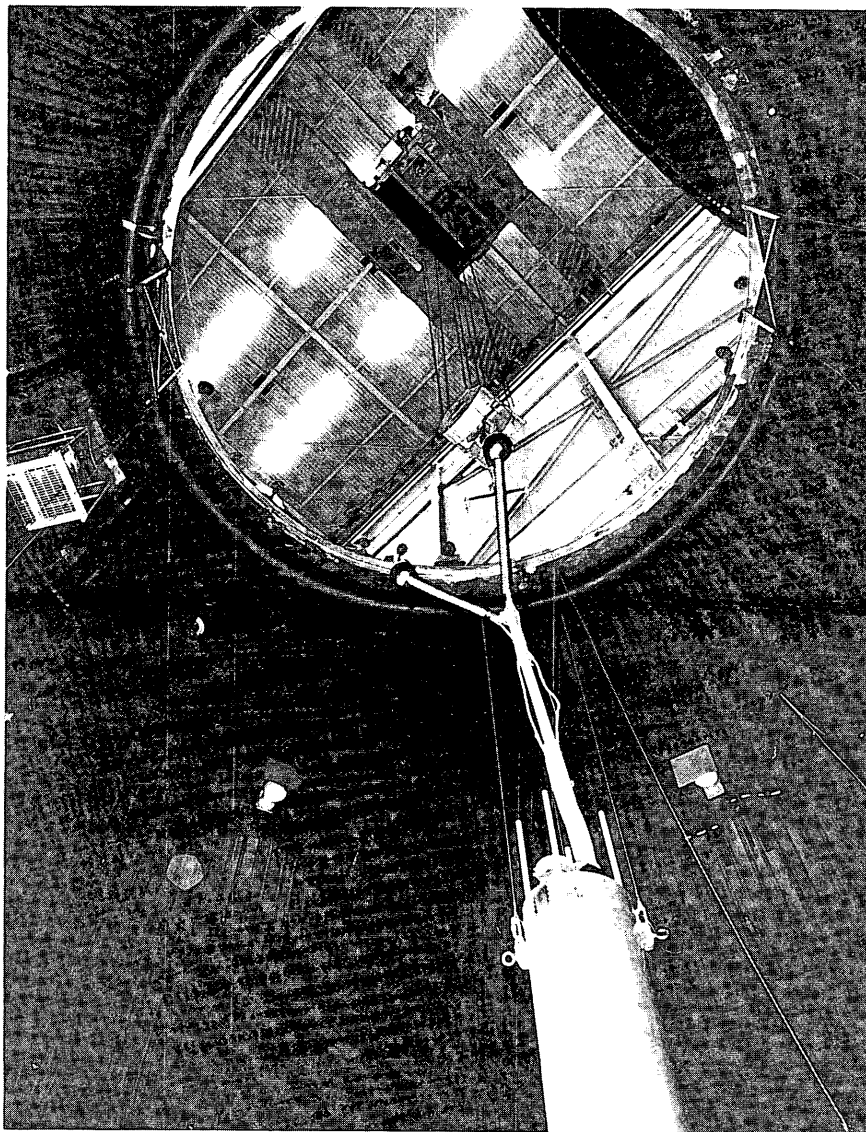
SPEAR-1 was flown in December 1987; SPEAR-2 is scheduled for early 1990. The maximum voltage on SPEAR-1 was 44,000 V, and SPEAR-2 is planned for 100,000 V. Surfaces with these voltage levels have never been tested in a plasma environment, either in space or in ground tests. Ground tests were crucial to project the behavior expected in flight for the SPEAR-1 experiment. Ground

tests are also expected to play a similar role for the SPEAR-2 experiment.

NASA Lewis has unique vacuum facilities for doing tests like these at its Plum Brook Station. The B-2 vacuum facility is 11.6 m in diameter

and 19.5 m long. The Space Power Facility is 36.6 m in diameter and 36.6 m long. The large test volume is essential for proper simulation of the plasma environment. Normally, these facilities provide only a simulated vacuum environment of the neutral gas in low Earth orbit

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*SPEAR-1 in B-2 facility*

(pressure of approximately  $1 \times 10^{-5}$  torr). However, for the SPEAR tests both vacuum facilities were specially equipped to simulate the plasma density of the low-Earth-orbit environment. SPEAR-1 flight results showed that a ground test in the B-2 facility is a good simulation of the space environment. The SPEAR-1 ground test predicted that noncatastrophic discharges would be seen in flight, and this prediction was confirmed by the in-space data.

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Funding source: DOD

### Solar Array Module Plasma Interaction Experiment

The solar array module plasma interaction experiment (SAMPIE) is an international, cooperative endeavor between NASA and the European Space Agency. SAMPIE will be designed to explore the environmental effects between the low-Earth-orbit space plasma and solar array modules that are biased to large potential differences with respect to the plasma. The objectives of SAMPIE will be to determine the voltage thresholds at which arcing occurs on the solar array test modules as well as the arc rates and strengths, to determine the plasma current collection characteristics of the solar array test modules, and to measure a set of basic plasma parameters to aid in data analysis. Future spacecraft designs and structures will push the operating limits of module technology; SAMPIE will provide key information necessary for optimum module design and construction.

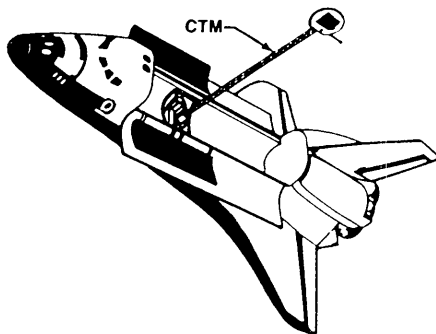
Negotiations between NASA and the European Space Agency (ESA) for a

cooperative experiment regarding environmental effects culminated in a fiscal 1989 start for this effort. Both agencies are currently developing conceptual designs for an experiment to be carried aboard the space shuttle. SAMPIE will use two state-of-the-art solar modules, possibly with gallium arsenide or indium phosphide solar cells, to determine environmental effects.

The ESA work is being done at the Technology Centre (ESTEC) and is focused on providing one of the two solar modules to be used and on developing the collapsible tube mast (CTM). The CTM will move the solar modules up to 15 m away from the shuttle to allow various ram and wake plasma effects of the shuttle to be studied.

The NASA effort is being implemented by Lewis. With SAMPIE, Lewis continues its lead role in investigating solar cell-space plasma environmental effects, which in the past had culminated in the PIX I, PIX II, and SPHINX flight experiments. Lewis will provide the remaining solar module and develop the overall system design for the experiment.

The work will be performed in house, with a combination of civil service and engineering contractor staff. A flight experiment review will be held in early fiscal 1990. The SAMPIE experiment is currently scheduled for launch in November 1994.



*Solar array module plasma interaction experiment*

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## Radiation Effects on High-Power, Solid-State Switches

The effects of neutron and gamma irradiation on the electrical and switching characteristics of high-power, solid-state switches are largely unknown. The SP-100 space power system will require solid-state switches and other electronic components for missions lasting 7 to 10 years. Switches with high radiation resistance will enable a reduction either in shielding mass or in the distance between the reactor and the electrical circuits.

NASA Lewis has begun a program to experimentally and analytically address both the separate and combined effects of gamma and neutron irradiation and temperature. This program includes both in-house efforts and grant work at Wittenberg University. The Ohio State University research test reactor is used to conduct in-situ neutron irradiation experiments and the University of Cincinnati's Co-60 facility is used to conduct in-situ gamma irradiation experiments. The Co-60 facility at Sandia National Laboratory is also used.

Bipolar junction transistors (BJT's) with ratings of 450 V/50 A and 750 V/30 A and metal-oxide-semiconductor field-effect transistors (MOSFET's) with ratings of 200 V/30 A and 500 V/15 A have been investigated. BJT's are extremely sensitive to neutron irradiation; power MOSFET's are extremely sensitive to gamma irradiation. Other switches to be investigated include insulated gate transistors, static induction transistors, silicon-controlled rectifiers, and metal-oxide-semiconductor-controlled thyristors.

This experimental and analytical radiation program has expanded the knowledge of component and circuit lifetimes in terms of degradation and failure modes and has led to more specific knowledge of shielding requirements. This information has immediate application to the SP-100 ground engineering system presently under development.

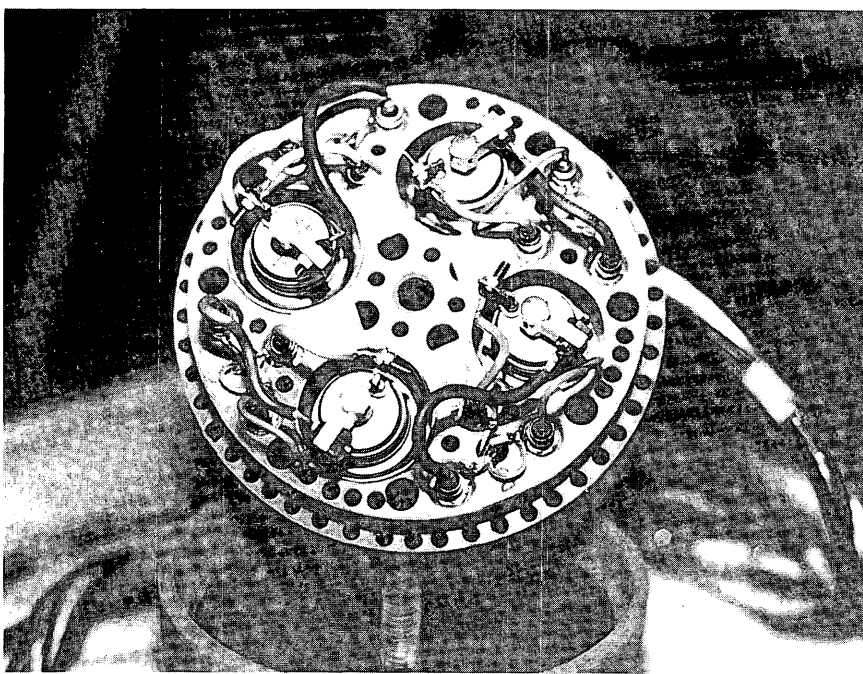
Frasca, A.J.; and Schwarze, G.E.: Neutron and Gamma Effects on the Electrical and Switching Characteristics of Power MOSFETS. Transactions, 6th Symposium on Space Nuclear Power Systems, Jan. 1989, Albuquerque, NM.

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*Radiation test fixture used for in-situ neutron and gamma radiation*

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### Photovoltaic Plasma Interaction Tests

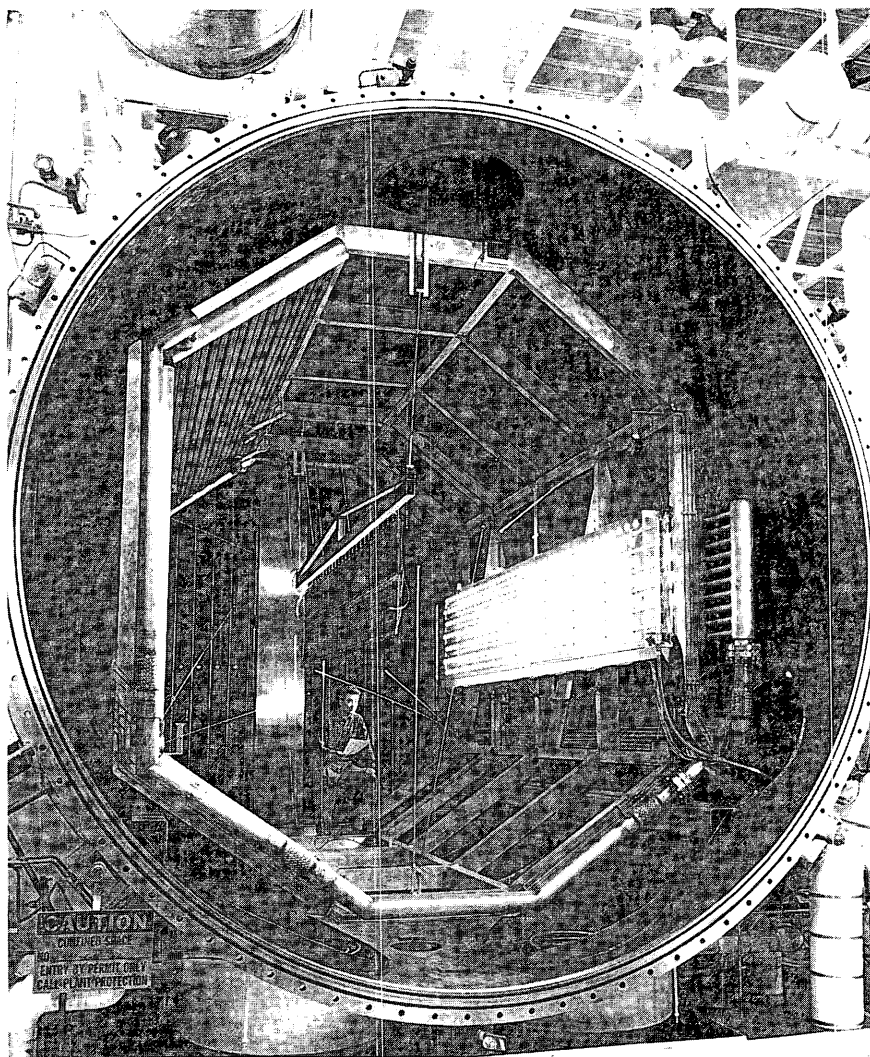
Space Station *Freedom* will operate in low Earth orbit in an environment consisting in part of plasma (electrons and ionized species). Little is known of the effects of the plasma environment on solar arrays operating at high voltages (160 V) and high power. Such potentially detrimental effects as arcing and the generation of parasitic currents may result in power loss. NASA Lewis has conducted photovoltaic plasma interaction tests to evaluate the effects of the plasma environment on the operating characteristics of the Space Station *Freedom* photovoltaic arrays. The series of five separate tests used a 400-solar-cell pair of panels manufactured by Lockheed Missiles and Space Co. All testing was done in tank 5 at the Electric Power Laboratory. This vacuum tank contains test fixtures, environmental controls, plasma sources, and instrumentation designed to simulate the relevant low-Earth-orbit parameters and to measure the response of the array.

In the first test parasitic current measurements were made at plasma densities of  $10^2$  to  $10^6$  ions/cm<sup>3</sup>. Plasma density in an equatorial orbit is expected to range between  $10^5$  and  $10^6$  ions/cm<sup>3</sup>. Data obtained from this test indicate that insignificant current loss resulted from operation in the plasma environment. The second test, charging effects, showed how higher electron flux in the polar orbit environment will affect the solar array. Preliminary results showed that array operation was not affected by high electron flux. During the third test the panels were biased negatively relative to the plasma potential to determine the array's arcing onset potential in the

expected plasma density range. Data from the fourth test, the out-of-eclipse simulation, will be used to show the expected voltage transient due to heating of the solar cells as the array moves into the sunlit portion of its orbit. The last test examined the dynamic response of the loaded solar array as it was switched between two loads. The response time is an important parameter used to design the sequential shunt unit component of

the photovoltaic array for the space station. Results indicate that the response time of the array is on the order of microseconds and is not affected by the range of plasma densities expected on orbit. These tests were completed in 1989.

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Array panels suspended in vacuum tank and illuminated by solar simulator

# Facility

## Space Station *Freedom* Modular Combustion Facility

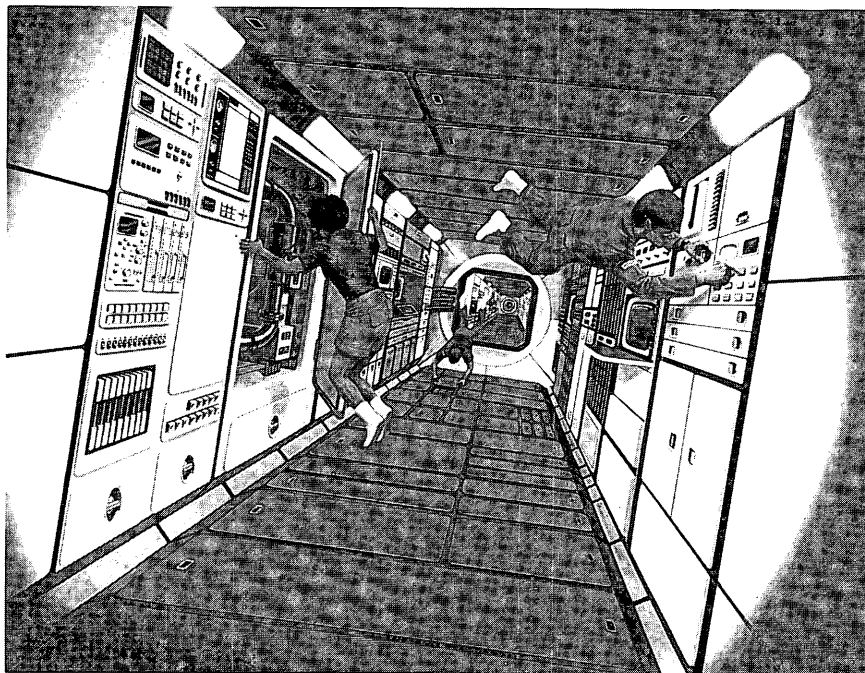
Space Station *Freedom*, scheduled to begin operation in the mid-1990's, will accommodate many different facilities for conducting a broad range of microgravity sciences. NASA Lewis is developing two of these facilities, for the combustion, fluid physics, and dynamics science disciplines. These modular multiuser research facilities will be available for use by the industrial, academic, and Government research communities.

The U.S. laboratory, with its facilities, will be unique because for the first time a permanently manned, multiuser laboratory in low Earth orbit will provide a long-duration microgravity environment along with appropriate resources and essential supporting services. These resources and supporting services, taken for granted in Earth-bound laboratories, historically have been difficult to provide for long spaceflight durations because of payload size and weight limitations.

The user-friendly combustion facility, called the Modular Combustion Facility, will support research experiments dealing with the study of combustion and its byproducts. Research into the mechanisms of combustion in the absence of gravity, with phenomena such as gravity-induced convection missing, will help provide a better understanding of the fundamentals of the combustion process. The knowledge gained will be applied to both Earth-based and space combustion technologies.

A study team made up of civil servants and support service contractors has been working on the definition study and conceptual

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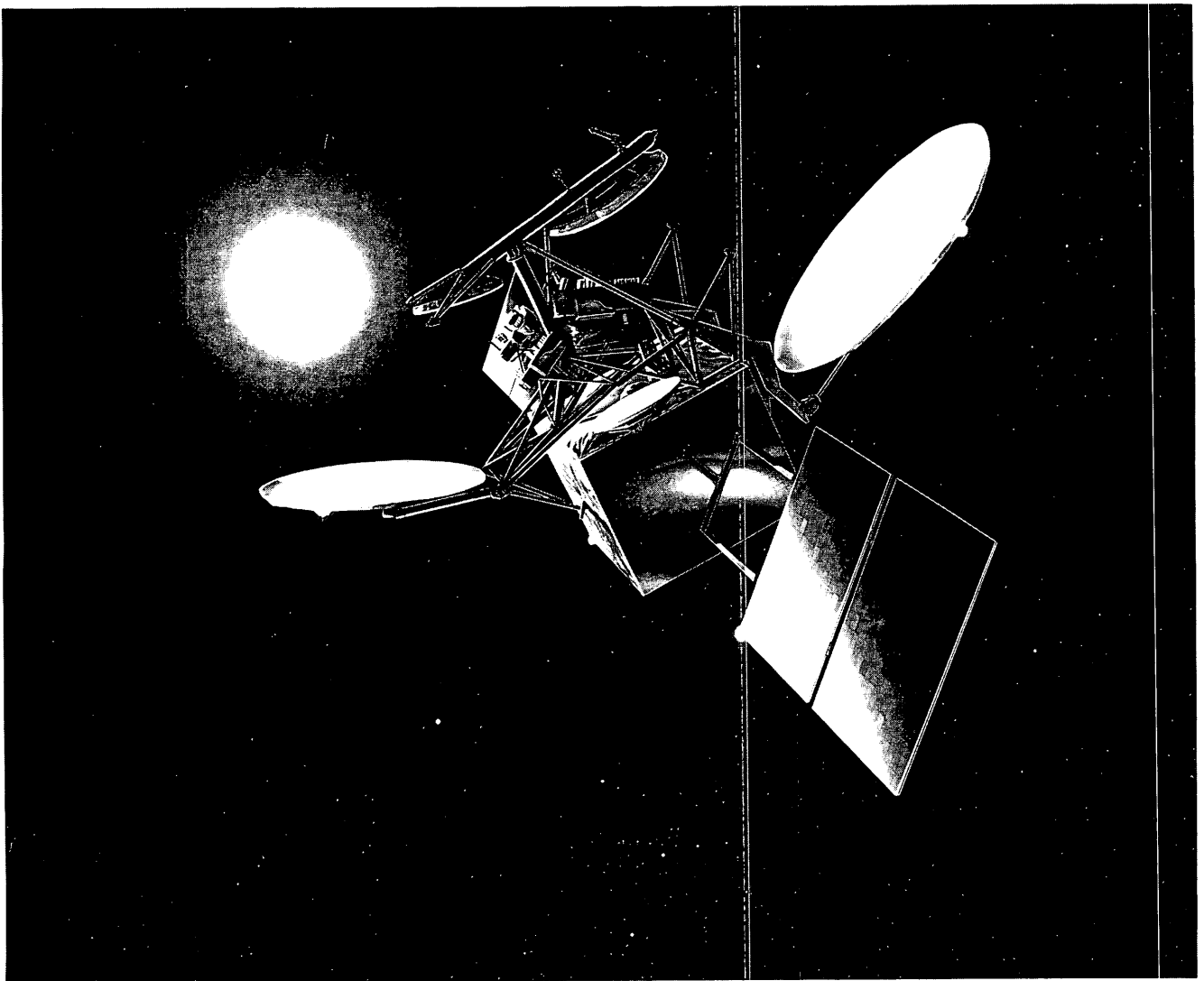
Artist's concept of U.S. laboratory on Space Station Freedom

design for this proposed facility. The objective of this study is to assess the facility's feasibility, effectiveness, and benefits to potential users. The study will also determine the philosophy or mode of accommodating combustion-related experiments on Space Station *Freedom* and propose a plan for developing the appropriate facility hardware.

A major project milestone was reached this year when an assessment workshop was held at Lewis. At this workshop a science and engineering panel made up of representatives from academia, industry, other NASA centers, and the European Space Agency reviewed the facility concept and development plans. This panel strongly endorsed microgravity combustion science,

agreed with the concept of facility modularity, and recommended the conceptual development of the facility. The project has been approved to proceed to a conceptual design review in early 1992.

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*Model of Advanced Communications Technology Satellite*

# Space Science & Applications

## Strategic Objectives

- To achieve a leadership position in the technologies associated with the in-space management of cryogenic fluids.
- To seek opportunities to vertically integrate cryogenic fluid technology by capturing a role in developing the subsystems for an on-orbit fuel depot.
- To be the principal NASA center for in-space microgravity science and technology experiments in power, propulsion, materials, combustion, fluid physics, structures, and electronics/communications.
- To successfully complete the Advanced Communications Technology Satellite Project in order to keep the United States preeminent in the communications industry.
- To be the NASA center responsible for the development of any future Centaur-derived upper stages and to remain a principal NASA manager of unmanned launch vehicles.

# Programs

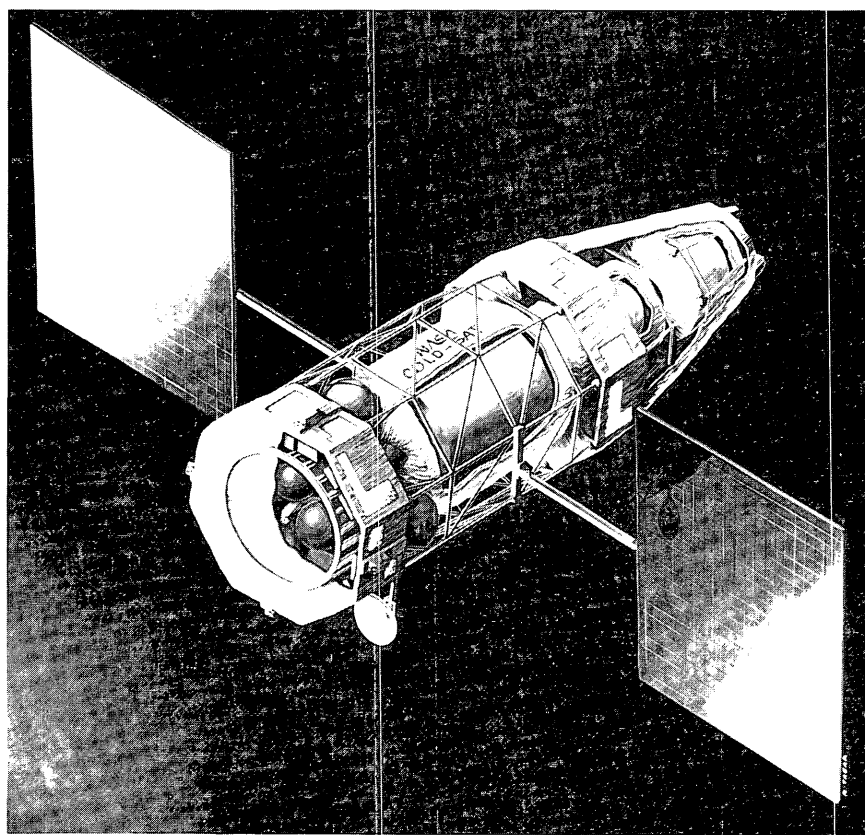
## Cryogenic Fluid Management in Space

Future NASA and Department of Defense mission models include spacecraft that will be carried into orbit without cryogenic fluids to minimize weight and to optimize thermal performance. The cryogenic fluids will be transported separately to orbit and then transferred to the spacecraft in the low-gravity environment of space. Cryogenic liquids will be valuable in other space applications as well. For example, the useful life of space experiments and satellites can be extended if they are refueled periodically with cryogenic fluids that have been stored in a space depot. Because of these varied needs for cryogenic fluids, their management is a critical part of the technology base that must be developed before longer-term program goals—such as a lunar base, a manned Mars mission, or a Mars sample return mission—can be reached. NASA Lewis has undertaken a program to develop the technologies essential for efficiently managing subcritical cryogenic fluids in the low gravity of space. A technology development spacecraft, COLD-SAT (Cryogenic On-Orbit Liquid Depot—Storage, Acquisition, and Transfer), has been proposed to perform cryogenic fluid management experiments after being launched into a low Earth orbit on an expendable launch vehicle. COLD-SAT will be designed for a 6- to 12-month life in orbit.

Fiscal 1989 marked the completion of the first year of three parallel COLD-SAT feasibility studies that had been awarded to Ball Aerospace/McDonnell Douglas/Boeing, Martin Marietta, and General Dynamics/Ford Aerospace. The purpose of these studies is to provide system

concept development; experiment, spacecraft, and system analysis; conceptual and preliminary COLD-SAT designs; mission design, establishing overall development plans; and cost estimates for the COLD-SAT project. Seven major subsystems were identified during the first year of the feasibility studies as being necessary for the successful operation of the COLD-SAT: attitude control; propulsion; structure; telemetry, tracking, and command; thermal control; electric power; and experiment. The studies will continue into fiscal 1991 as the contractors refine their experimental concepts.

The free-flying COLD-SAT spacecraft will be used for a series of cryogenic fluid management experiments. Broad technology areas include liquid storage, storing tanks of cryogenics in space subcritically for a few hours to several years while minimizing boiloff and controlling tank pressure; liquid supply, delivering single-phase liquid from the storage tank to a user; and liquid transfer, transferring liquid from a storage tank to a receiver tank under nearly weightless conditions while minimizing liquid losses and controlling receiver tank pressure. Also of interest are the performance



*COLD-SAT spacecraft*

### Advanced Communications Technology Satellite

of advanced instrumentation such as leak detection, flowmeters, and quantity gages and fluid-handling problems such as liquid sloshing and tank venting and dumping.

Individual experiments are planned to investigate the fluid physics and thermodynamics important in the processes associated with these technologies. The data obtained are to be compared with analytical models currently being developed. The established data base and the validated models will provide system designers with the tools necessary to configure future operational systems in orbit.

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In 1989 the ACTS project produced the major portion of the hardware assemblies and software modules that will form the flight spacecraft and the ground system. ACTS successfully progressed through the design phase into manufacturing and the start of integration and testing. This year's completion of the contract restructuring task, begun in 1988, clarified and strengthened the team effort of the General Electric Astro-Space Division, the prime contractor for the spacecraft, and COMSAT, the prime contractor for the NASA ground station and the master control station.

A critical feature of satellite technology being developed specifically for ACTS will allow for communications between extremely small ground terminals (1.8-m antenna diameter) located directly on customers' premises and will have throughput of 1.544 Mbps (24 voice or data circuits). The ACTS satellite, with onboard circuit switching and processing and high-gain spot antenna beams, will provide services for networks containing thousands of ground terminals. The communications capacity for the operational ACTS is three times larger than any conventional satellite capacity for the same weight in orbit. Thus, the ACTS system potentially offers significantly lower communications service costs.

Significant progress was achieved this year with the completion of certain key ACTS hardware assemblies. Motorola shipped the engineering model of the baseband processor, along with its special test equipment, to GE Astro in February after it had successfully completed all of the unit acceptance testing. The baseband

processor, perhaps the most unique feature of ACTS, demodulates high-speed bursts of uplink digital traffic, stores the baseband data, and routes individual messages to a different set of bursts for the downlink. The engineering model baseband processor is now being integrated with other equipment to form the engineering model communications electronics package. GE Astro will complete testing of this fully integrated engineering model prior to delivery to COMSAT by early 1990 for ground station verification. The flight model baseband processor is nearly completed at Motorola with scheduled delivery in late 1989.

Two other significant elements of flight hardware were also delivered to GE Astro this past year. Watkins-Johnson completed and delivered all of the 46-W, 20-GHz traveling-wave tubes for the ACTS spacecraft. These tubes are being integrated with the GE-provided electronic power conditioners to form the power transmitters essential to all satellite communications. Electromagnetic Sciences completed and delivered to GE Astro the beam-forming networks, or complex microwave feed assemblies, that will form the electronically hopping multiple spot beams on ACTS.

Critical design reviews for the multi-beam antenna and the spacecraft bus were completed and fabrication is under way. Composite materials are being used for the antenna support assembly, which must withstand extreme temperature gradients and at the same time be able to hold within precise limits the positions of the 3- and 2.2-m antenna reflectors, along with the subreflectors and the

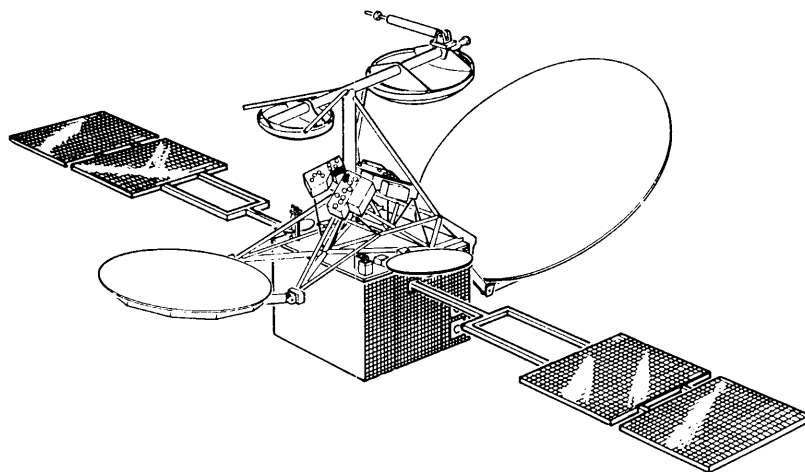
multiple feed horn assemblies. The numerous subsystems of the bus are in manufacturing, and integration and testing are expected to begin in early 1990.

Work on the NASA ground station and master control station is progressing at COMSAT. Critical design reviews of the master control station and the network control portions have been completed. A major milestone was achieved with the delivery of the 54-W, 30-GHz traveling-wave-tube amplifier—the primary component of the transmitting side of the NASA ground station. Hughes has completed this vital hardware and delivered it to COMSAT for integration and testing with the remaining portion of the ground station's radiofrequency terminal.

NASA Lewis is designing and building a high-burst-rate ground station for testing and evaluating the link parameters associated with the microwave switch matrix on the spacecraft. Many components have already been built and the system integration is under way.

Fiscal 1990 will be a crucial year for ACTS. Component delivery by all subcontractors, combined with the completion of manufacturing by GE Astro, will lead to the integration of the bus and communications payload subsystems. Spacecraft integration of these subsystems will be the final stage in preparing for spacecraft testing. These activities at GE Astro will parallel similar integration efforts at both COMSAT and Lewis as ACTS approaches its May 1992 launch.

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*ACTS spacecraft*



# Research & Technology

## Structural Mechanics

### Microgravity Robotics Technology

NASA Lewis is developing actuators, robot concepts, and control strategies to provide smooth motion, to minimize reaction, and to control acceleration in the microgravity laboratory environment.

Two related motion control problems are associated with the operation of robots in microgravity. The first involves the transport of specimens without exceeding predefined microgravity acceleration limits. The second involves the transport of other objects relatively quickly while minimizing reaction forces transmitted to the robot's surroundings through attachment points. The simplest solution to both problems is to move the robot arm so slowly that accelerations and forces are maintained within acceptable limits. A better approach is to use mechanisms and control strategies that are inherently smooth or that compensate for reactions, or both. These techniques will improve robot productivity in the space laboratory.

Roller, or traction, drives significantly benefit robotic applications by providing smooth operation and eliminating backlash. Lewis is attempting to determine the suitability of traction drives for space robot applications, to measure critical material- and environment-related performance parameters, and to exploit their beneficial characteristics by developing suitable traction-driven robot joint concepts.

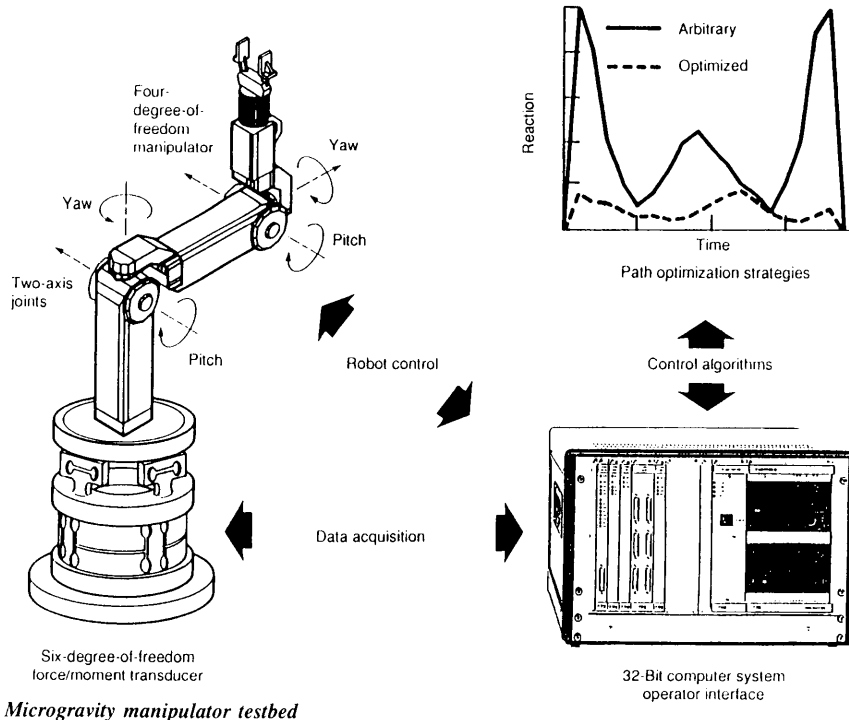
The design of a robot roller drive depends on the traction performance (traction coefficient, load capacity, wear rate, fatigue life, etc.) of the selected materials and roller config-

urations. These in turn depend on operating conditions. A unique test rig will be used to investigate the effects of these operating conditions on material performance. These tests will aid in understanding roller contact phenomena in nonatmospheric environments as well as provide data to design future roller-driven robot actuators.

The dynamics and control research, a cooperative effort between NASA Lewis, Case Western Reserve University, and Carnegie Mellon University, has focused on the operation of a robot while limiting transmission of base reactions to the surrounding environment. Manipulators used in space applications will, in general, have kinematic redundancy to facilitate the performance of tasks. For example,

redundancy will be required to avoid obstacles and singular configurations. In certain applications the redundant degrees of freedom can also be used to minimize base reactions. In simplest terms, moving the additional sections of the manipulator in a direction inertially opposite to the movement of the end effector minimizes the base reactions.

In the procedures developed thus far an optimization strategy identifies the joint motions that will minimize the resulting base reactions. The joint trajectory strategies were incorporated into a general computer program to simulate and control manipulators with any number of links, joints, and degrees of redundancy. Results show that it is possible to design manipulators



## Microgravity Physics

capable of operating with minimal base reactions.

A microgravity manipulator testbed is being constructed to demonstrate the specialized control strategies and to assess the performance of roller-driven joints. The main features of this demonstrator are a four-degree-of-freedom traction-driven robot arm, a base reaction sensor, and a control computer. Future efforts will include evaluation of real-time feedback of reaction forces for improved base reaction compensation, measurement of end-effector acceleration and vibration, and experimental evaluation of advanced drive mechanisms.

### Bibliography

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Lewis contacts: Douglas A. Rohn, (216) 433-3325; and Dr. Charles Lawrence, (216) 433-6048

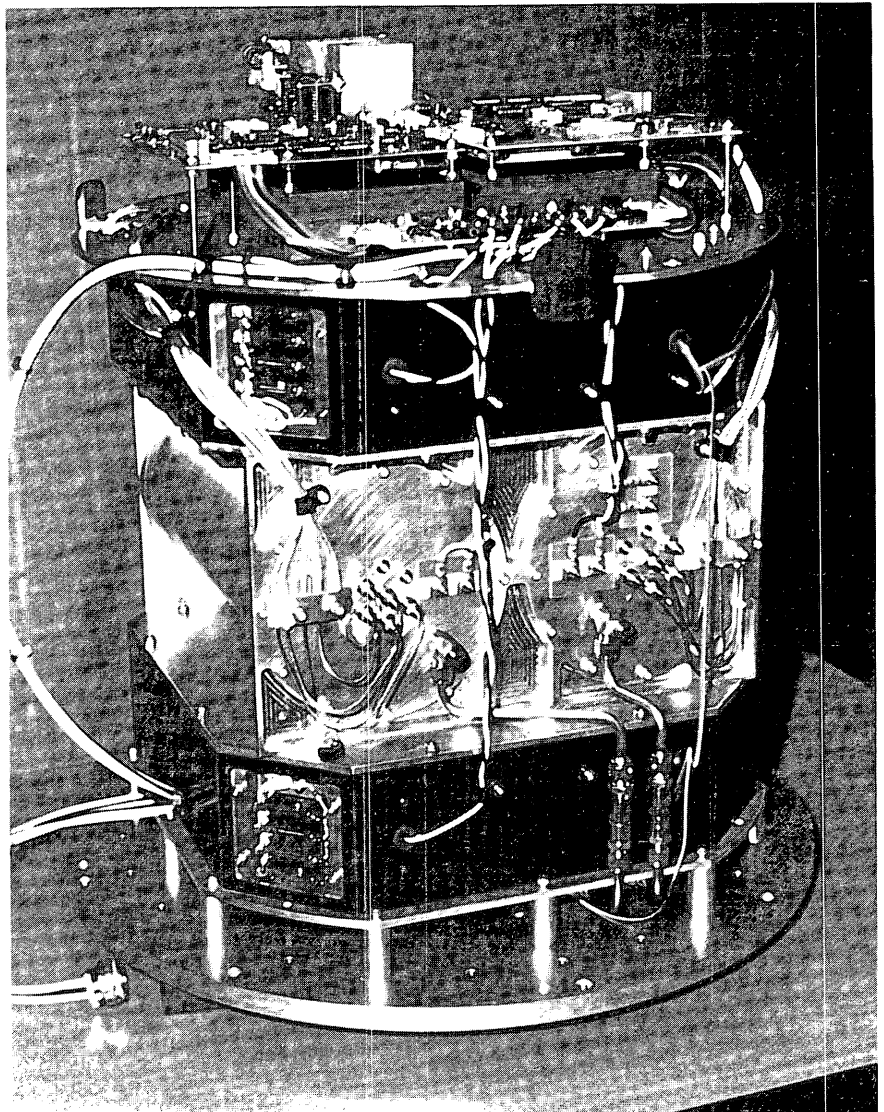
Headquarters program office: OAST

### GaAs Crystal Growth Experiment

Gallium arsenide (GaAs) substrates and devices are considered a leading contender for a new generation of electronics technology offering greater speed and durability than existing silicon-based systems. High-quality crystals of GaAs are difficult to produce, and the crystal growth of this material is of significant interest.

The effect of buoyancy-driven convection on the types and distribution of defects in GaAs is the focus of a study being conducted by GTE Laboratories, Inc. The work is cost shared by GTE, the Air Force Materials Laboratory, and the Microgravity Science and Applications Division of OSSA. NASA Lewis

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*Self-contained, dual-furnace payload for GaAs crystal growth experiment*

manages the project, has implemented numerical modeling of the furnace and fluid flow, and will characterize selected samples from the study.

The study, as proposed by the principal investigator, James Kafalas, consists of a systematic investigation of the effect of gravity-driven fluid flow on GaAs crystal growth and will include GaAs crystal growth in the microgravity environment on the space shuttle. A comparative study of crystal growth will be made under a variety of Earth-based conditions with variable orientation (to change the direction of the gravity vector) and applied magnetic field (to partially damp flow) in addition to the microgravity growth. Earth-based growth will be performed under stabilizing as well as destabilizing temperature gradients. The boules grown in space and on Earth will be fully characterized to correlate the degree of convection with the distribution of impurities. Both macro- and microsegregation of dopant will be determined.

The experimental hardware has been designed and fabricated by a GTE team led by Alfred Bellows. The space growth experiment will be flown in a self-contained payload container through NASA's Get-Away Special (GAS) Program. The advantages of using the GAS program are simplicity of manifesting the payload onboard the orbiter, frequent flight opportunities, quick turnaround (necessary for iterative experiments), and low cost. The payload with its large alkaline battery power source will include two redundant experimental systems with separate well-insulated growth furnaces. The samples are approximately 1 in. in

diameter and 4 in. long. Each sequentially scheduled growth experiment will require approximately 8 hours to complete, and collected data will include micro-acceleration, temperature, and furnace power. The use of the specially designed growth ampoule and furnace system for both space- and Earth-based growth experiments will lend validity to the comparative studies and simplify the numerical modeling of the furnace and the ampoule.

Development and testing of the flight hardware is nearing completion at GTE, and safety and engineering documentation will be completed by the end of 1989. A potential flight opportunity in August 1990 has been identified in the current space shuttle manifest.

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**Headquarters program office: OSSA**

### **Isothermal Dendritic Growth Experiment**

The isothermal dendritic growth experiment (IDGE), to be conducted onboard the space shuttle beginning in 1993, will test fundamental theories that describe dendritic freezing of liquid metals on Earth. Rensselaer Polytechnic Institute scientists proposed the experiment to NASA. NASA Lewis then designed and is fabricating and testing the spaceflight apparatus.

The IDGE flight apparatus will acquire data needed to correct current theories that predict metal dendrite growth kinetics during the freezing process. Experimentation on Earth has had limited success because gravitationally driven convective effects cannot be separated from conductive and diffusive effects. Since steel, aluminum, and superalloys freeze dendritically, IDGE results should lead to improvement of their Earth-based production.

The unique shuttle-carried flight apparatus will automatically conduct 25 dendritic growth experiments per spaceflight. Three flights are planned for 1993 to 1996 on the NASA Marshall Space Flight Center-managed USMP experiment carrier. Two will involve succinonitrile (a transparent material having a crystal structure similar to iron), and one will involve pivalic acid (a transparent material having a crystal structure similar to nickel).

A high-fidelity engineering copy of the IDGE flight apparatus has been built at Lewis. Tests of the engineering copy indicate that the flight apparatus will meet all scientific and engineering requirements. In realistic tests at Lewis the copy survived simulated shuttle launch stresses and

then was able to automatically carry out dendritic growth experiments. During the experiments it maintained growth temperatures accurately to within 0.002 Kelvin, automatically detected growing dendrites by analyzing slow-scan television images, and acquired dozens of dendrite photographs. In addition, aspects of the IDGE communications to Earth, which include slow-scan television images of growing dendrites, were successfully simulated.

Fabrication of the IDGE flight apparatus will begin in 1990.

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Winsa, E.A., et al.: Flight Hardware and Tele-Operations Supporting the Isothermal Dendritic Growth Experiment Aboard the Space Shuttle, *AIAA paper 89-0863*, Jan. 1989.

**Lewis contact:** Edward A. Winsa,  
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**Headquarters program office:** OSSA

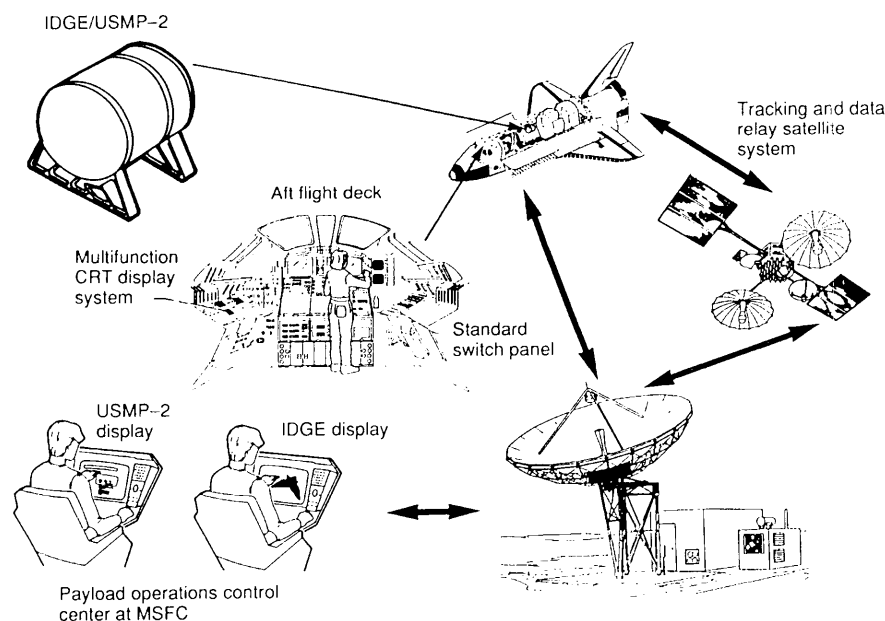
#### Vibration Isolation Technology for Microgravity Science Experiments

The microgravity environment of space offers a unique opportunity to do science experiments that benefit from the lack of gravitational effects. To do so effectively requires an environment that is free not only of gravitational effects but also of other random and time-dependent disturbances. However, inherent in the normal operation of the space shuttle and eventually Space Station

*Freedom* is the generation of random and time-dependent disturbances that can adversely affect the success of these experiments. This creates the need to understand the effects of residual accelerations on experiments and to reduce the effect of these disturbances to an acceptable level. The Vibration Isolation Technology (VIT) Project is addressing this concern. The VIT project, managed by NASA Lewis, has as its objective the development of the technology to provide a controlled, well-characterized, low-gravity environment for sensitive microgravity science experiments.

The VIT project has three major elements: (1) the analysis of selected experiments to define the effects of residual accelerations and to determine realistic requirements, (2) the development of reactionless mechanisms and robotics for use in a controlled microgravity environment, and (3) the development of vibration isolation and damping technology to maintain the required environment for microgravity science experiments.

The NASA Marshall Space Flight Center, in conjunction with the University of Alabama at Huntsville, is analyzing selected experiments. This effort began in July 1988.



*Teleoperation of isothermal dendritic growth experiment*

Navier-Stokes computational methods are being used to model the effects of disturbances on thermocapillary convection of open cavities and float zones, the effect of bouyancy forces on the convective transport diffusion coefficient, and the stability of the bridge shape in containerless liquid bridges. In addition, they are making order-of-magnitude estimates of fluid sensitivity to disturbances as a function of amplitude and frequency.

NASA Lewis is developing reactionless mechanisms and robotics for microgravity science experiments. The work is being done in house and by contracts and grants. The focus of this effort is to develop the technology to provide acceleration control for robotic mechanisms within specific experiments as well

as for manipulation on or around experiments. The technical objectives are to optimize the kinematic and dynamic performance of mechanisms and robotic manipulators, to evaluate roller drives for mechanical actuation systems, to study linear single-degree-of-freedom reactionless mechanisms, to develop a microgravity manipulation technology testbed, and then to demonstrate the technology on a ground-based experiment. A grant with Carnegie-Mellon University resulted in improved trajectory optimization algorithms. A grant with Case Western Reserve University showed that a robot with two redundant degrees of freedom would reduce the base reaction force and moment function to zero. In house at Lewis a single-degree-of-freedom reactionless roller drive mechanism

has been fabricated and is being evaluated. Under contract Teledyne Brown has evaluated the user needs, benefits, and integration of robotic systems in the space station Microgravity and Materials Processing Facility.

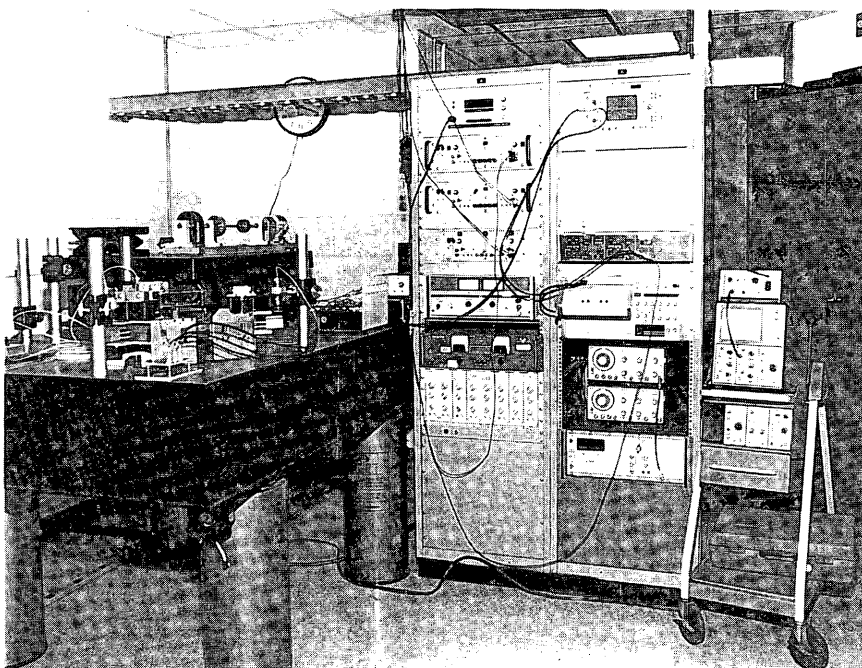
The isolation and damping technology effort is focusing on developing low-frequency actuator technology and associated active control strategies. A magnetics laboratory has been established at Lewis to build and test active magnetic suspension systems. A multiple-degree-of-freedom suspension system has been built and is now undergoing evaluation. An isolation testbed system is in fabrication. This system will be installed in the Lewis Learjet and used to evaluate active and passive isolation systems and components in a low-gravity environment. Under grant the University of Virginia is developing advanced actuator technology for microgravity science applications, and Pennsylvania State University is developing digital active control algorithms for maintaining a microgravity environment in space.

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*Laboratory setup for evaluating multiple-degree-of-freedom vibration isolation system*

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## Tank Pressure Control Experiment

The tank pressure control experiment will study the fluid dynamics and thermodynamics of jet-induced fluid mixing in low gravity. This experiment, using Freon as the test fluid, will produce data critical to the design of on-orbit cryogenic storage and resupply systems. The expanding U.S. space program will in the future rely extensively on on-orbit use of subcritical cryogens for propellants and life-support systems. In-space experimentation is needed to obtain the data required to design low-gravity storage and handling systems for the successful management of these fluids in orbit. The experiment definition and preliminary design have been completed, and the payload accommodations requirements document has been submitted to NASA. The tank pressure control experiment is scheduled to fly on the space shuttle in early 1991. The contractor is Boeing Aerospace.

The experiment will obtain video and numerical data on the fluid dynamics of jet-induced, two-phase fluid motion within a tank in low gravity for application to controlling tank pressure in future on-orbit cryogen storage and resupply systems. Other objectives are to evaluate the applicability of existing empirical mixing models and correlations to thermal mixing in low gravity and, if appropriate, derive new or modified correlations, and to identify approaches for enhancing the ECLIPSE computer code (now under development) for simulating two-phase fluid dynamics and thermodynamics.

The experiment will simulate the behavior of cryogens in a low-gravity environment by using Freon at saturated conditions as the test

fluid. Pressure, temperature, and video data will be collected as the liquid in the test tank is alternately stratified with heaters and mixed with a pump. The payload carrier will be a Get-Away Special container, and shuttle integration will be done within the Complex Autonomous Payloads Program.

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## Modeling of Propellant Reorientation

Washington University in St. Louis, under a grant from NASA Lewis, has completed a study of propellant motion under reorientation maneuvers. These maneuvers are designed to settle propellants over tank outlets prior to main engine restarts after a period of zero-gravity coasting. For this study Washington University developed a computer code known as Energy Calculation for Liquid Propellants in a Space Environment (ECLIPSE). The fluid dynamics portion of ECLIPSE is handled by the VOF-2D (Volume of Fluid) code developed at Los Alamos National Laboratory under an interagency agreement with NASA Lewis. The ECLIPSE code agreed reasonably well with drop tower data. Parametric investigations were then conducted on the effects of varying settling thrust levels and propellant tank size. An optimized thrust level reduced fuel usage by a factor of 20 over standard practice. These studies also confirmed the applicability of extrapolating the drop tower work (done in tanks under 4 cm diameter) to tanks of 92, 106, and even 427 cm diameter. Accelerations investigated ranged from  $10^{-4}$  to  $1 \text{ cm/sec}^2$ .

Also investigated was whether reorientation by continuous thrusting could be replaced by short bursts from a larger thruster. Since thrusters are usually available in discrete sizes and the small thrusters required for optimum settling of most space systems are not currently available, this is particularly important for implementing the study results on real space systems. Tanks of the same size and shape as those used in the continuous-thrust studies were used. Thrusters capable of producing continuous accelerations of 7.85,

0.981, and 0.0981  $\text{cm/sec}^2$  were pulsed to produce effective accelerations ranging from  $10^{-5}$  to 2.36  $\text{cm/sec}^2$ . Results indicate that the pulsed settling technique duplicates continuous thruster settling over most of the acceleration range tested.

Future efforts will include improving code stability at lower thrust levels by refining the surface tension model and planning low-gravity experiments to verify the computational results. A reference manual and users guide for the ECLIPSE code are being prepared so that the code can be made available to the aerospace community.

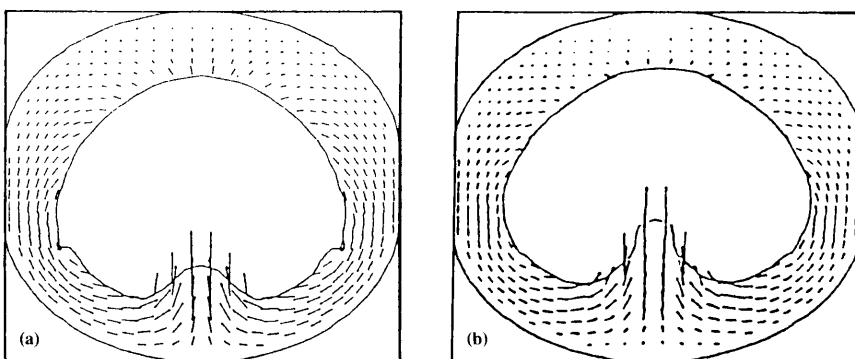
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### Surface-Tension-Driven Convection Experiment

Materials processing that involves solidification and crystal growth is generally expected to be dramatically improved in the microgravity environment of space because natural convection and buoyancy effects are eliminated. However, convection currents due to surface tension forces are still present. These thermocapillary flows result from the fluid motions generated by the surface-tractive force that is caused by surface tension variations due to the temperature gradient along the free surface.

Changes in the nature and extent of these thermocapillary flows can cause deleterious fluid oscillations. Numerical modeling is not adequate to predict the parameters for which these oscillations occur because of an inherent coupling between the imposed thermal signature, the surface flow, and the surface deformation. In order to complete an understanding of the physical process and to develop an accurate numerical model, experimental data must be obtained in an extended low-gravity environment. Therefore, the surface-tension-driven convection experiment (STDCE) was proposed for the space shuttle.

The STDCE consists of a container, 4 in. in diameter by 2 in. deep, filled with silicone oil to provide both a flat and a curved free surface that can be centrally heated either externally or internally. The cross section is illuminated by a 1-mm-thick sheet of light; the scattering of this light from micrometer-sized aluminum oxide particles mixed into the oil allows the axisymmetric flow velocities to be observed.



Propellant position in 371-cm by 427-cm tank (a) after 150 sec of continuous 0.0196- $\text{cm/sec}^2$  acceleration, (b) after 200 sec of thrust pulsed to produce effective acceleration of 1.18  $\text{cm/sec}^2$

The design and development of the STDCE flight hardware is an in-house project. Major components are being flight-qualified under contract: an infrared thermal imager for mapping the surface temperature gradients, a carbon dioxide laser for surface heating, a laser diode system for illumination, and an intensified video camera for measuring fluid motion. These components will be integrated with the mechanical, optical, electrical, electronic, and structural systems that will be designed, fabricated, and tested at NASA Lewis.

The current goal is to have experiment hardware ready for shipment to the NASA Kennedy Space Center by May 1, 1991, for integration into a double rack of the Spacelab module for the USML-1 mission on March 26, 1992. Technical information exchange meetings have been held during 1989 with the USML-1 payload mission team at the NASA Marshall Space Flight Center.

The preliminary design review was completed in May 1989, with NASA Marshall acceptance of the baseline experiment requirements document and the phase 1 safety compliance data package. Two engineering models of the STDCE were built at Lewis to test its design functionality and its ability to withstand shuttle launch vibrations. Design changes were made to accommodate the change from a single- to a double-rack configuration. Flight hardware qualification at Lewis is planned for 1990 after approval of the final design at the critical design review in December 1989.

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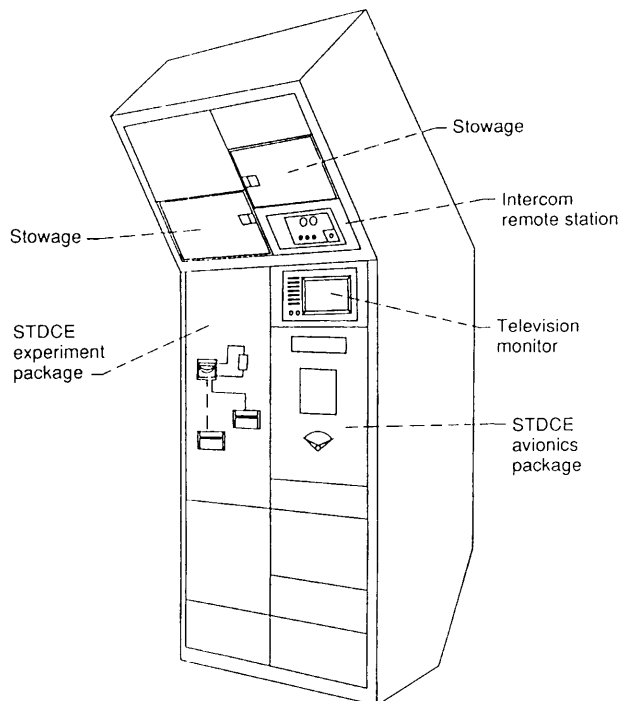
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*Surface-tension-driven convection experiment in Spacelab double rack*



## Critical Fluid Thermal Equilibration Experiment

Gravity can obscure interesting physical phenomena or even block all experimental techniques for making a desired measurement. The feverish activity in fluid critical phenomena of the 1970's slowed to a near standstill in part due to gravitational limitations on acquiring further experimental data closer to the critical temperature. The availability of low gravity on longer and longer duration space missions has brought experimental efforts back to life. In fact, a recent international workshop sponsored by NASA and the National Institute for Standards and Technology (NIST, formerly the National Bureau of Standards) concluded that the unexpected behavior of near-critical fluids in low gravity has brought equilibration dynamics to the fore as a frontier in critical phenomena research.

Any pure fluid has a liquid-vapor critical point. For states with either temperature, pressure, or density greater than the critical values, liquid and vapor are no longer distinguishable. At the critical point a fluid is confused as to whether it is liquid or vapor. Consequently, it is singularly compressible.

Such compressibility is the root of the troubles caused by gravity. The weight of a constant-volume sample of fluid loaded on average to the critical density is enough to compress half of the sample to a density above the critical density, leaving the other half below the critical density. Only a thin portion between the two halves is at the critical density. The closer to the critical temperature, the more compressible the fluid, and the thinner is the critical zone. At some temperature the zone is too small for

any known experimental probe to be used to measure thermodynamic properties. Low gravity reduces the weight of the fluid on itself and widens the critical zone for a given temperature. Or best of all, it allows one to go closer to the critical temperature before experimental probe limits are reached.

Another key fact about near-critical fluids is that the time for a sample to reach thermal equilibrium approaches infinity as the critical point is approached. This necessitates long-duration experiments in space, and the uncertainty as to the appropriate time scales has itself spawned scientific interest.

The critical fluid thermal equilibration experiment being developed here at Lewis involves a small constant-volume sample of sulfur-hexafluoride thermostated with milli-Kelvin control near its critical temperature of 45.54 °C and observed via interferometry, visualization, and transmission. The scientific objectives are (1) to observe large-phase-domain homogenization without and

with stirring, time evolution of heat and mass after a temperature step applied to a one-phase equilibrium sample, phase evolution and configuration upon going to two phases from a one-phase equilibrium, the effects of stirring on a low-g two-phase configuration, and two-phase to one-phase heating dynamics starting from a two-phase low-g configuration and (2) to quantify the mass and thermal homogenization time constant of a one-phase system under logarithmic temperature steps.

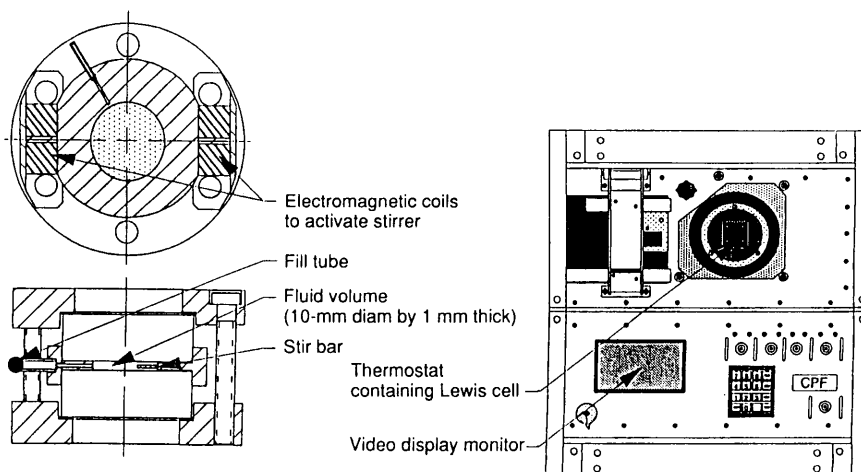
This experiment is manifested for a December 1990 shuttle flight. Two equivalent sample cells will be integrated into the European Space Agency Critical Point Facility.

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Shuttle experiment on critical fluid thermal equilibration: (a) Lewis cell, (b) ESA facility

# Combustion

## Zero-Gravity Droplet Combustion

Understanding the basic physical mechanisms in the combustion of single, nearly motionless hydrocarbon fuel droplets without the masking influences of buoyancy will allow better analytical models to be constructed. Therefore, tests are being conducted to study droplet burning rates and droplet extinction diameters. (Extinction is caused by the shorter fuel vapor residence time at small droplet diameters.) The analytical models provide some of the building blocks for computer models of fuel spray systems. The results, besides aiding understanding of fire safety in space systems, will be used to obtain better performance, higher efficiencies, and lower pollutant emissions in future gas turbine and other commercial systems.

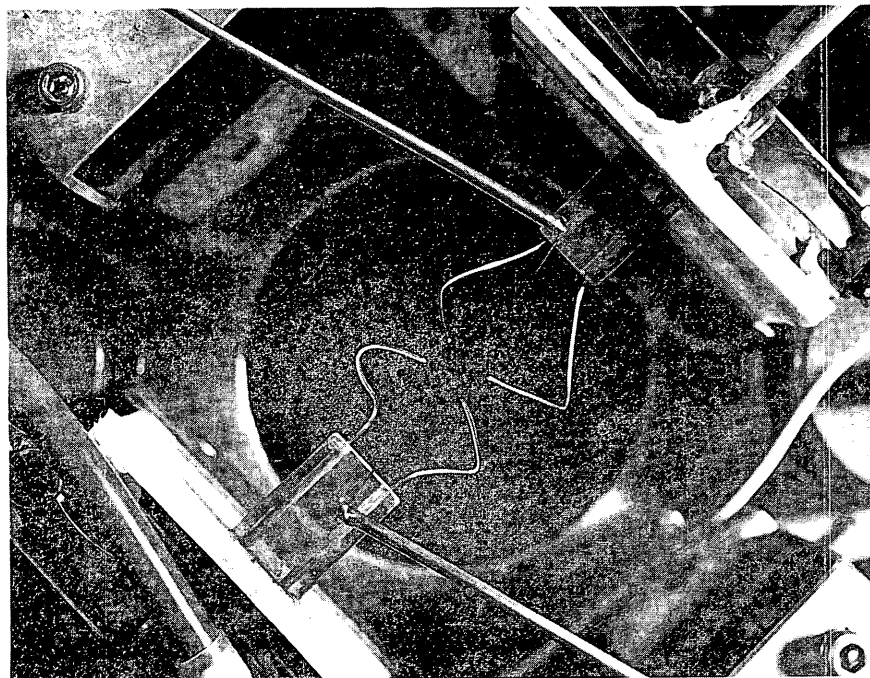
The analytical model development and experimental data analysis are being done by Professors Forman Williams of the University of California-San Diego and Frederick Dryer of Princeton University. Key to experimental success has been the development of a method to grow, deploy, and ignite droplets without imparting substantial motion to them. TRW of Redondo Beach, California, has developed an opposed-needle system with symmetric sparking electrodes around the droplet. This system has been extensively tested, refined, and used in experiments in the 2.2- and 5-sec Lewis drop towers.

In 1989 a testing program of 120 data points was started in the 5-sec

Zero-Gravity Facility. Three fuels (decane, heptane, and methanol) will be studied over a range of test chamber oxygen mole fractions (0.18 to 0.50) and pressures (0.5 to 2 atm). The decane-in-air study was recently completed. A fully transient, spherically symmetric computer model, with detailed chemistry for methanol only, has also been developed. The model supports the drop tower test findings and is significantly better than the classical quasi-steady models for this fuel. Burning rates for heptane in air obtained from these tests disagree with previously reported results, possibly because of differences between tests, particularly in initial conditions. This will be explored in the immediate future.

A principal aim of this effort is to provide a strong justification for a space shuttle flight experiment.

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*Setup for 2.2-sec droplet combustion experiment*

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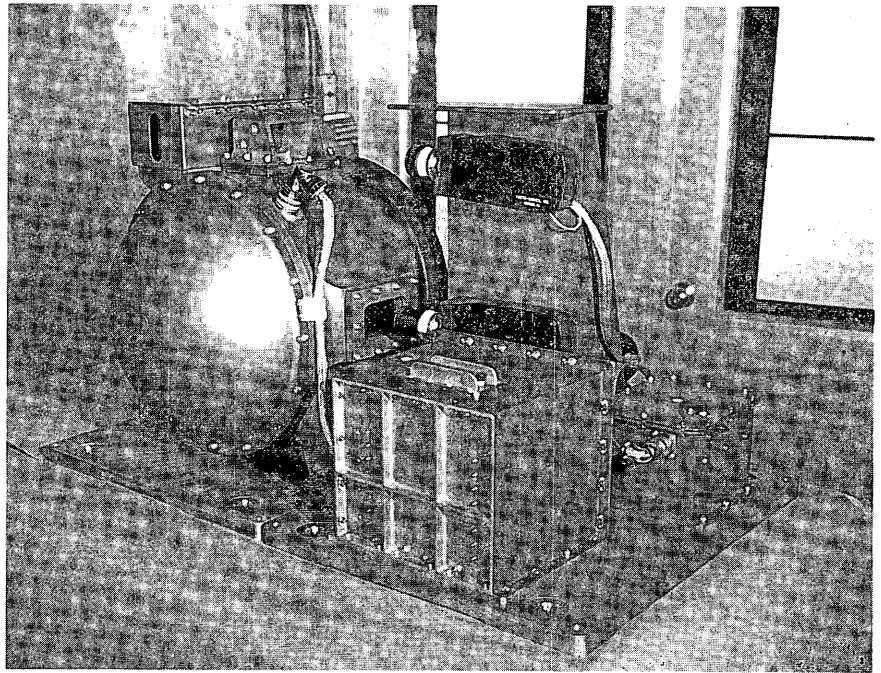
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## Solid-Surface Combustion Experiment

The solid-surface combustion experiment (SSCE) is the first of a series of microgravity space shuttle experiments being implemented by NASA Lewis. Lewis researchers recognized that the extended periods of microgravity available on the space shuttle orbiter could provide a unique laboratory environment for combustion research. The absence of any significant gravitational field facilitates observation of fundamental combustion mechanisms that cannot be directly observed in Earthbound experiments because of gravitational settling or buoyancy-driven convection processes. The understanding of combustion processes in terrestrial systems, particularly processes involving diffusion, can be enhanced by this research, since data from the microgravity experiments can be compared with the analytical predictions of models with the gravity-controlled factors removed. Clean experiment boundary conditions can also be uniquely obtained in the near absence of gravity.

The SSCE, which was originally proposed by Dr. Robert A. Altenkirch, currently of Mississippi University, as a part of NASA's Physics and Chemistry Experiments (PACE) Program, is designed to provide data on flame spreading over solid surfaces in a quiescent microgravity environment. Two important geometrical configurations arise. In the first case, termed "thermally thin," the fuel is too thin to support a temperature gradient across its thickness, and the dominant heat transfer mode becomes gas-phase conduction ahead of the flame. In the second case, termed "thermally thick," the fuel is thick enough for a transverse temperature gradient to

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*Setup for solid surface combustion experiment*

occur, and solid-phase conduction becomes important to forward heat transfer. Under microgravity conditions, natural convection is severely curtailed and fuel-air mixing depends on the secondary mechanisms of the local Stefan flow and molecular diffusion.

In the first phase of the flight program the thermally thin case will be studied using ashless filter paper as the fuel. A variety of environmental conditions inside the combustion chamber will be tested. The second experiment phase will cover the thermally thick case and use polymethylmethacrylate as the fuel.

The SSCE hardware consists of two modules, a combustion chamber module and a camera module, con-

figured in a block of four mid-deck locker spaces. To meet flammability restrictions, the combustion chamber windows are made from Lexan polycarbonate bonded to optically clear sapphire, with the sapphire surface on the interior of the chamber. Environmental conditions of up to 98 percent oxygen can be provided inside the chamber without causing a flammability hazard for any chamber materials. The operating pressure of the SSCE chamber is 2 atm, and the chamber is hermetically sealed.

The camera module contains the data acquisition and control system, a battery pack, two motion picture cameras, and an electric power filter for the cameras. Two views of the experiment are provided by the

optical system with the two 16-mm motion picture cameras. Spatial resolution of less than 0.1 mm is obtained with this system.

The SSCE flight hardware has been completed. Currently, the experiment is being integrated to fly as a shuttle mid-deck experiment and on several Spacelab missions as a SMIDEX rack experiment.

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### Particle Cloud Combustion in Reduced Gravity

The study of combustible particle clouds is of fundamental scientific interest as well as practical concern. Such clouds serve to spread fires in underground mining operations and contribute to the fire and explosion hazards of grain storage and handling facilities. Of particular scientific interest is an understanding of the characteristic combustion properties, especially flame structure, propagation rates, and the effects of stoichiometry.

A ground-based feasibility program has been completed by conducting tests in the NASA Lewis Learjet. For fuel-rich mixtures, quasi-steady flame propagation through a 5-cm-diameter, 60-cm-long tube was observed. The observed shapes of the flame front and wake structures were as anticipated but had not been previously obtained. Of greatest scientific interest was the finding that for near-stoichiometric mixtures, a new mode of flame propagation was observed, now called a chattering flame. A theory developed by the

project's principal investigator, Professor Abraham L. Berlad of the University of California-San Diego, suggests that the flame acoustically segregates the fuel into fuel-rich and fuel-lean laminae and then radiation from combustion products heats successive fuel-rich laminae sufficiently to cause autoignition.

The ongoing research effort will continue in the NASA Lewis Learjet, examining pulverized coals and inert particle clouds.

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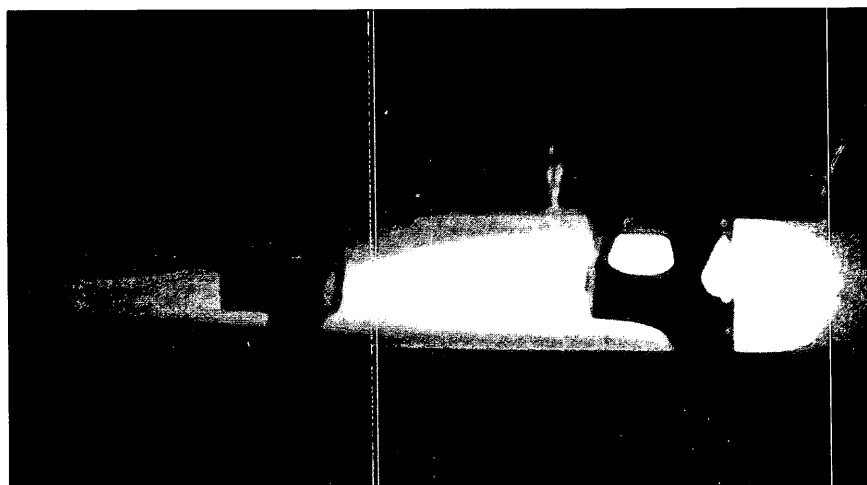
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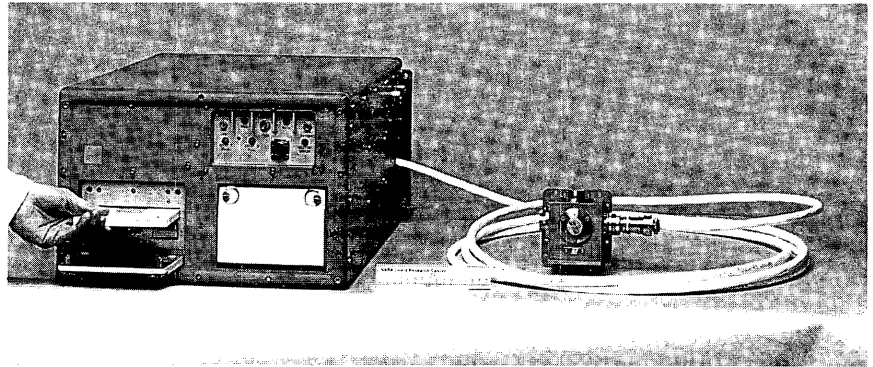
*Flame propagation through a fuel-rich mixture in reduced gravity*

## Instrumentation

### Space Acceleration Measurement System

A variety of space shuttle orbiter experiments are currently under design or development as part of OSSA's Microgravity Science and Applications Program and OAST's In-Space Experiments Program. These experiments generally require measuring and recording low-gravity accelerations during space operations. Such measurements made to date have proven to be inadequate (e.g., in terms of data rate, sensitivity, and accuracy). As a result, OSSA in 1986 assigned NASA Lewis the responsibility of developing a space acceleration measurement system (SAMS) capable of serving a wide variety of space experiments.

The design of this system takes into consideration requirements for microgravity experiments located in the shuttle orbiter mid-deck and cargo bay and in Spacelab. In addition to measuring, conditioning, and recording accelerations the system will be capable of performing complex calculations and interactive control. The main components consist of a remote triaxial sensor head (up to three per unit), a microprocessor-driven data acquisition system, and an optical disk data storage device (up to seven per unit). In operation, the triaxial sensor head produces output signals in response to acceleration inputs. These signals are amplified, filtered, and converted into digital data that are then transferred to optical disk data storage. The system design is modular so that both the software and the hardware can be upgraded as technology advances. The electronics package employs complementary metal oxide semiconductor technology and a modular interconnection system.



SAMS hardware

The resultant SAMS unit is a compact, lightweight, low-power instrument capable of measuring microgravity accelerations at three experiment sites simultaneously. With its state-of-the-art components the SAMS unit can sample at rates up to 500 samples per second and record 200 megabytes of data before operator intervention. Typical shuttle missions result in 5 gigabytes of data.

The SAMS project is managed and implemented by a team of Lewis and support service contractor (Sverdrup Technology, Inc.) personnel. Eight complete acceleration measurement flight systems will be built, tested, and flown under this project. This includes the design and implementation of all corresponding software, safety and integration documentation, and ground support hardware. As part of the software development effort, the SAMS project team will implement user-driven requirements for specific experiments and will develop and supply, as required, the SAMS data-reduction software package.

The engineering unit for two SAMS configurations (viz, the Spacelab

center aisle and the shuttle mid-deck) is currently being qualified. Assembly of the initial flight units is in progress. The first mission for SAMS is scheduled for August 1990. According to current schedules the first flight unit will be ready for a preshipment review by February 1990.

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## Microgravity Fluids and Combustion Diagnostics

Microgravity Fluids and Combustion Diagnostics (MFCD), an advanced technology development project, applies existing and new diagnostic techniques to the development of advanced measurement systems for determining species concentration profiles, temperature and velocity fields, and other parameters for space experiments in fluids and combustion. The diagnostic development activities also augment the low-gravity, ground-based fluids and combustion experiments that support the corresponding flight projects. The ground-based facilities include drop towers as well as aircraft flying parabolic trajectories. The value of the planned microgravity fluids and combustion experiments depends heavily upon the ability to measure the experimental parameters accurately without perturbing the process under study. Optical diagnostics, in general, are the most feasible means of doing this. All measurement systems must contend with the severe limitations of space experiments in size, weight, power, data acquisition, storage and processing, and operator expertise, along with strict demands on safety. The system must also be sufficiently robust to withstand launch vibrations. These demands and restrictions tend to promote the development of minimally complex instruments.

The project consists of three concurrent phases. In the first phase the science requirements of the individual experiments, current and planned, are determined along with the diagnostic techniques most capable of satisfying these requirements. Relevant criteria are then applied to determine which techniques are appropriate for development. Criteria include technical

feasibility, range of applicability, relative risk, and realism of schedules and resources. The information gathered is constantly updated, with special attention to recent optical measurement techniques, particularly in solid-state devices. The development plan is periodically reviewed by outside experts and by participants at appropriate workshops.

In the second phase the selected diagnostic techniques are bread-boarded in the research laboratories at Lewis. Currently, three full-field visualization techniques—reactive seeding, intensified array detectors, and color schlieren photography—are being developed to visualize reactions where luminosity is too weak to observe by conventional methods. An example of reactive seeding is the introduction of titanium tetrachloride into the gas stream or ambient atmosphere surrounding the burner or sample. This vapor spontaneously reacts with water vapor formed in the reaction zone to form titanium dioxide particles. Mie scattering from incident planar illumination is imaged onto a photographic medium, thus demarcating the flame front and its rate of progress. Direct imaging of the reaction zone by spectrally filtered intensified imaging provides four to five orders of magnitude in optical gain. Luminous regions can be filtered out, rendering the flame front clearly visible.

Advantages of the color schlieren technique over the conventional knife-edge schlieren technique include independently variable sensitivity, dynamic range, and the use of continuously graded filters of the appropriate spatial dimensions to

minimize the effects of diffraction. The system optics are compressed without sacrificing sensitivity by employing catoptric lensing. Two Rayleigh scattering techniques for measuring combustion gas temperatures and densities are being developed, either of which will allow the effect of background contributions to the scattered signal to be subtracted without a priori calibration procedures. One method is simultaneous multiple wavelength scattering, and the other is spectrally resolved imaging. Multiple wavelength scattering exploits the specific dependence of the Rayleigh scattered signal on wavelength. Spectrally resolved imaging directly measures the line width broadening of the scattered signal. The Rayleigh scattered line width depends on the temperature due to the Doppler shift from moving molecules. The translational velocity giving rise to the observed Doppler shift is, in turn, linked to the absolute temperature by the Maxwell-Boltzmann distribution.

One computational and one theoretical effort are being supported in house as part of this project. The computational effort analyzes particle image velocimetry (PIV) data. The recipient of an R&D 100 award, the computational analysis yields vector field velocities of fluids by a direct vector search of successive occurrences of particle images. The objective is to determine the full field velocity limits in the Young's fringe method for particle image velocimetry by a comprehensive development of the statistics that describe the resultant fringe field. The results of this effort will provide researchers with the optimum configurations for conducting their PIV experiments, as well as

### High-Resolution, High-Frame-Rate Video Technology

the limiting accuracies for these measurements.

The matured breadboarded diagnostics are then reconfigured and mated to ground-based, low-gravity experiments in the third phase, with emphasis on the support of flight projects. Two flight projects are presently being supported: the solid surface combustion experiment (SSCE) and the surface-tension-driven convection experiment (STDCE). In SSCE an intensified array camera will be mated to an engineering model of the combustion apparatus and flown aboard the Learjet to visualize and record the combustion rate of paper samples under low luminosity. In STDCE the flow velocities in silicon oil in a thermal gradient will be computed by Young's fringe method. The SSCE effort is scheduled for completion in January 1990.

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High-resolution, high-frame-rate video technology (HHVT) is an advanced technology development project to enhance microgravity science experiments requiring high-speed, detailed optical data. HHVT would reduce some of the data storage, management, and transmission constraints imposed on experimenters by today's film recording and video technologies. HHVT could also give an experimenter on the ground more control over an experiment in flight. Potential benefactors of HHVT are microgravity experimenters, largely in combustion science, fluid physics, and materials science.

User requirements and technology capability surveys have indicated that the imaging requirements of some microgravity experiments exceed the capabilities of state-of-the-art video system components, especially image sensors. For this reason three parallel development efforts are being pursued. First, in order to allow microgravity experimenters to make the most efficient use of high-speed film cameras and commercially available video cameras, the HHVT project team is designing video event trigger circuits that will allow experimenters to capture just those events of interest on film or videotape. Experimenters currently use sizable amounts of film to monitor experiments before a scientific event of interest occurs. Often these events last only a second or less. The video event trigger circuits will alert the data acquisition system for a particular experiment that the key event to be recorded has or is about to occur (based on a change in pixel density or some other experiment property). The event will then be recorded in time on film or

videotape. The video event trigger circuits will be designed to work with a high-speed (1000 frames/sec), high-resolution (1024- by 1024-pixel array) video camera and will be simplified to work with commercial video or film cameras.

Second, NASA Lewis will acquire, integrate, and test a developmental HHVT system. The camera head for this system will have high resolution (1024 by 1024 pixels), the ability to address pixels, the ability to do sub-framing, which involves scanning regions of interest smaller than the full 1024-by-1024 frame, and high framing rates (up to 2300 frames/sec for a 128-by-128 subframe). Video data will be acquired at the rate of 40 million pixels/sec and transferred into a high-speed, temporary data storage device. The data can then be displayed on a terminal, routed to a large-capacity magnetic tape recorder, or discarded. Having the developmental HHVT system in the laboratory will allow the engineers and microgravity experimenters at Lewis to use the video system with actual experiments, to debug the system, and to design necessary improvements before writing the specifications for a flight version. The HHVT project team is currently acquiring the components for the developmental video system. All of the components are expected to be ready for integration in the HHVT laboratory by April 1991.

Third, NASA Lewis will acquire, integrate, and test a baseline HHVT system. The baseline HHVT camera will feature 1024- by 1024-pixel resolution, pixel addressability, and subframing. It will also offer higher frame rates and better image quality

# Facilities

than the developmental camera is expected to have. Specifications for a state-of-the-art, solid-state camera have been written.

Members of the HHVT project team participated in the Joint Services High Speed, High Definition Video Workshop, June 27 to 29, 1989, at Eglin Air Force Base. The purpose of the workshop was to coordinate the various high-speed, high-resolution video camera development efforts of different Government agencies. The organizers of the workshop and attendees acknowledged that NASA Lewis is a leader in defining the imaging requirements of its users and in designing a powerful, flexible video system to meet those requirements.

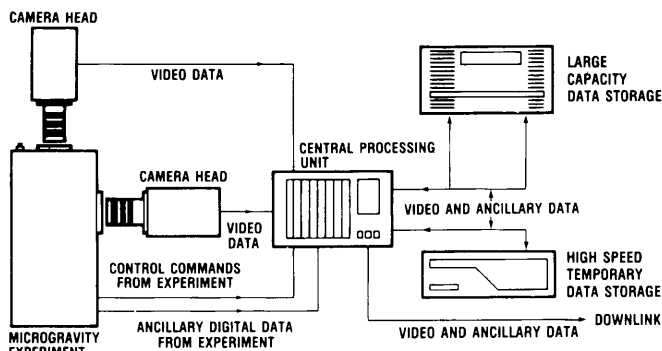
Lewis contacts: Marlene S. Metzinger,  
(216) 433-2851; and William K. Thompson,  
(216) 433-2638  
Headquarters program office: OSSA

## Liquid-Nitrogen-Flow Test Facility

Cell 13 of the Rocket Laboratory has been rehabilitated to provide a liquid-nitrogen test facility for developing various cryogenic fluid management technologies. General areas to be investigated include tank chilldown, no-vent fill, thermal stratification, jet-induced mixing, and advanced instrumentation. The initial planned tests will characterize the process of vapor condensation on liquid sprays and provide data on the quenching of flat plates with liquid sprays. The technologies under development support NASA's Cryogenic Fluid Depot Program, a vital part of Project Pathfinder.

The test facility comprises a liquid-nitrogen supply dewar, a vaporizer to provide saturated nitrogen vapor, an insulated test tank, and an ESCORT II data acquisition system. The supply dewar for the test tank contains 300 gal of liquid nitrogen at a maximum pressure of 150 psig. Liquid nitrogen is brought to the test tank through four supply lines. One of these lines is routed through the coils of a copper cooling jacket and thus inhibits heat leaks into the tank. The jacket is sandwiched between the insulation and the outer surface of the tank. The remaining supply lines are routed through vacuum-jacketed piping and are sized for delivery of various nitrogen flow rates.

A 9-kW vaporizer on one of the supply lines can provide vapor to the tank as the test fluid. A turbine meter, located on the tank drain line, is used to measure the tank liquid mass outflow rate. The test tank is constructed of 304 stainless steel and is moderately insulated with urethane foam. The fluid motion within the tank can be monitored through two

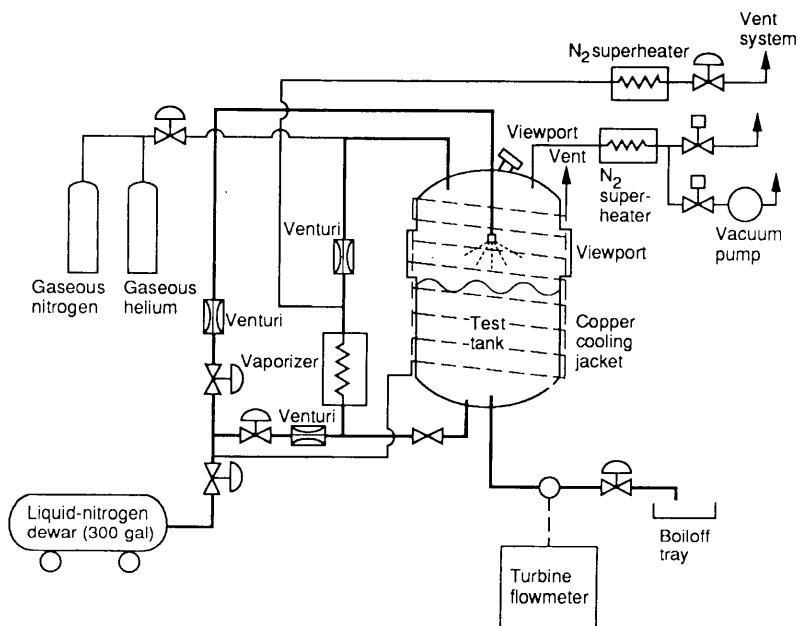


*High-resolution, high-frame-rate video*



6-in. quartz window viewports; a 2-in. quartz window mounted on the top dished head provides a video camera viewport. An ESCORT II data system is used for gathering both the facility and test hardware data.

Lewis contact: Naseem Saiyed,  
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Headquarters program office: OAST



Setup for liquid-nitrogen flow test

### Reactivation of Cryogenic Propellant Tank Research Facility

NASA Lewis has begun ground-based testing of large-scale cryogenic fluid management systems for in-space applications at the reactivated Cryogenic Propellant Tank Research Facility (K-Site) located at the Plum Brook Station in Sandusky, Ohio. Tests will be conducted at approximately 6-month intervals from 1989 to 1993. Thirty-two specific cryogenic fluid management technologies have been identified for development to meet future NASA needs for the efficient and effective management of subcritical cryogenic fluids in space. K-Site is uniquely suitable for large-scale cryogenic hydrogen experiments in transfer line chill-down, tank chilldown, no-vent fill, thermal stratification, jet-induced mixing, passive and active thermodynamic venting, pressurization, and thermal performance.

K-Site was decommissioned in 1974 after 8 years of serving as NASA's primary test area for cryogenic propellant tank research. During the last quarter of 1987, NASA funded a study that included inspection and operation of portions of the facility and its supporting subsystems. The study revealed that the facility was in excellent condition. An 18-month effort was started on March 15, 1988, to bring the facility to a fully operational status. The major portion of the work was to refurbish the subsystem flow components, to install a modern data system, to upgrade the facility to meet current safety standards, and to enhance the physical appearance of the control room and test chamber building.

During late 1989, preliminary testing began at K-Site. A series of 20 tests were planned to obtain data on tran-

sient chilldown, no-vent fill, thermal stratification, and pressurization. The test hardware is an 87-in.-diameter tank mounted in a 13-ft-diameter by 13-ft-high cryoshroud. The tank is insulated with 34 layers of multi-layer insulation; the number of layers used on the insulation system and the construction of the system are representative of the type of system that may be used on an orbit transfer vehicle.

The tank itself is an ellipsoidal volume of revolution of approximately 175 ft<sup>3</sup>. It is supported by 12 fiberglass composite struts within a stainless steel tubular framework. The entire tank and the framework are supported from the payload simulator, which serves as part of the top of the 13-ft by 13-ft cryoshroud.

Most fill and vent lines to the tank and instrumentation leads are brought

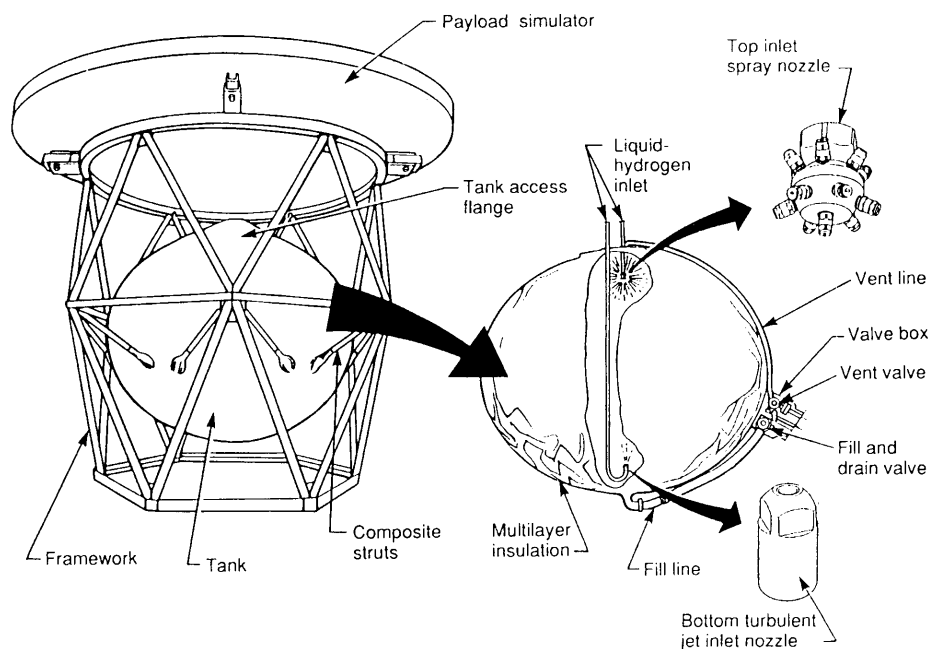
within the cryoshroud through a liquid-hydrogen cold guard in order to minimize heat leaks. A fill and drain line to the bottom of the tank is usable in either mode via valves located at the side of the tank. The bolted flange at the top has four smaller flanges that will accommodate a vapor vent line, fill lines, a liquid level probe, and an instrumentation feedthrough. A spray nozzle assembly, located internally at the top of the tank, consists of a cluster of 13 conical spray nozzles to produce a nearly isotropic liquid distribution. A nominal droplet size of 400  $\mu\text{m}$  is expected from this nozzle during testing.

The single jet nozzle at the bottom of the tank is rated to produce a 3/8-in.-diameter cylindrical jet with a velocity of 87 ft/sec at a nozzle pressure drop of 10 psi. Both the multiple-jet and single-jet nozzles are used for conducting no-vent fill of

the 175-ft<sup>3</sup> tank. Liquid hydrogen of known thermodynamic state can enter the tank through either the top or bottom fill lines.

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(216) 433-3852

Headquarters program office: OAST



*Configuration of 87-in.-diameter cryogenic propellant tank for preliminary testing*

## Ground-Based, Reduced-Gravity Research Facilities

The ground-based, reduced-gravity facilities (2.2-Second Drop Tower, Zero-Gravity Facility, and Learjet) at NASA Lewis experienced their most ambitious year in 1989 in terms of utilization (testing), number of experiments, number of researchers, and number of new experiment packages that were designed and fabricated. The 2.2-Second Drop Tower surpassed a major milestone as test drop number 9000 was executed. The 5.18-sec Zero-Gravity Facility has surpassed 2100 research drops. The Learjet has also supported the most programs ever during a fiscal year. Ten visiting scientists participated either independently or jointly with NASA investigators in the performance of NASA-sponsored research.

The ground-based facilities at Lewis have continued to play a vital role in the Microgravity Science and Applications Program as they provide the baseline, normal-gravity, and reduced-gravity data in support of a large number of broad-based in-house and sponsored programs. The facilities are used to execute ground-based science programs, to perform precursor tests to define the science requirements and conceptual designs of space experiments, and also to verify space experiment technology development. The research conducted in these facilities enhances the value and success of space experiments. It is anticipated that their importance will not diminish in the foreseeable future.

During 1989, over 900 research drops were performed in the 2.2-Second Drop Tower in support of 20 programs involving reduced-gravity research on combustion and

fluids. The inventory of experimental drop packages has increased from 4 to 16 over the last two years. Along with this numerical growth has come technological advancement. Onboard computers are now utilized on most of the experiments, and lasers and video cameras and recorders have also been implemented. These changes represent a major advance over the previous means of data acquisition, which was high-speed photography.

The Zero-Gravity Facility also was used extensively in 1989. Several major programs were supported as over 150 research drops were performed. Many of the experiments were built up or underwent extensive modification. The Zero-Gravity Operations Office, which is responsible for much of the engineering as

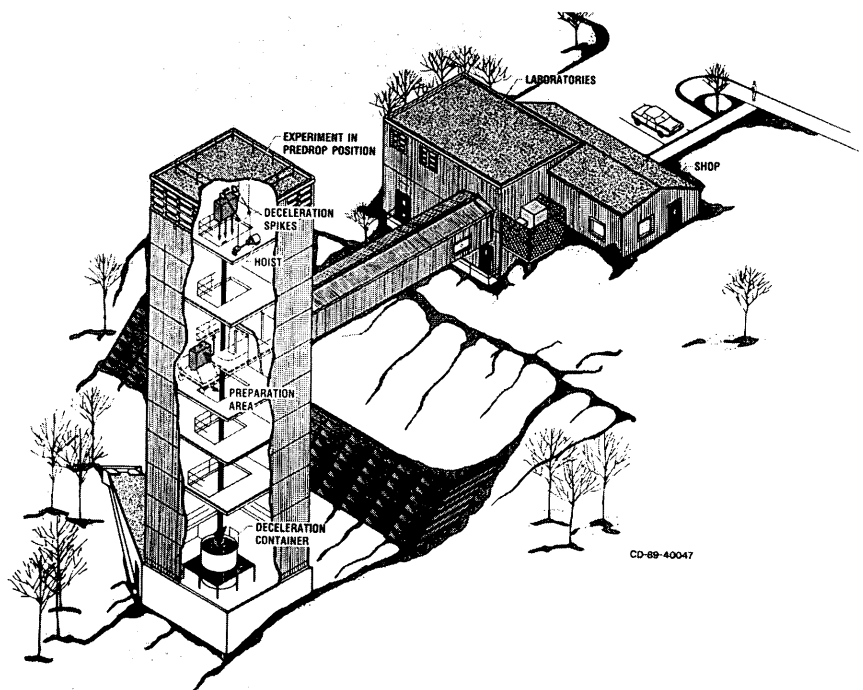
well as operations in the Zero-Gravity Facility and the Learjet, supported 39 experiments in fiscal 1989.

Some of the research supported by the Lewis ground-based microgravity facilities involves droplet combustion, gas diffusion flames, particle cloud combustion, pool fires, premixed gas combustion, two-phase flow, surface-tension-driven convection, and solid surface combustion.

### Bibliography

Lekan, Jack: Microgravity Research in NASA Ground-Based Facilities. AIAA Paper 89-0236, Jan. 1989.

Lewis contacts: Jack Lekan, (216) 433-3459; and Raymond G. Sotos, (216) 433-5485  
Headquarters program office: OSSA



2.2-Second Drop Tower including planned building modifications for fiscal 1990

## New Computational Materials Processing Laboratory

The application of computational techniques to materials science offers the possibility of improving processes, understanding complex interactions, designing more efficient experiments, and producing more reliable materials. A special laboratory for computational materials science has been created at NASA Lewis. This laboratory employs its own set of advanced graphics workstations and also connects directly with supercomputers at Lewis and elsewhere. Programs originally developed for computational fluid dynamics or for structural calculations have been modified to address the unique problems of materials processing. Materials problems typically involve the presence of free surfaces, the position of which must be calculated as part of the solution; this greatly complicates the boundary conditions and requires the development of new numerical algorithms.

The laboratory specializes in predicting the effects of gravitationally driven convection on crystal growth from the liquid and from the vapor. For example, nonuniformities in the chemical vapor deposition of silicon have been related to the convective flow patterns calculated for the chamber used. Further studies provide design guidance for deposition chambers. In another case, the fluid flow effects during the growth of gallium arsenide semiconductors in space have been modeled. Complex three-dimensional flows result when the residual acceleration vector is not aligned with the growth chamber axis.

Though still quite new, the Computational Materials Science Laboratory has attracted international

attention and received several requests to train industrial researchers in the techniques used.

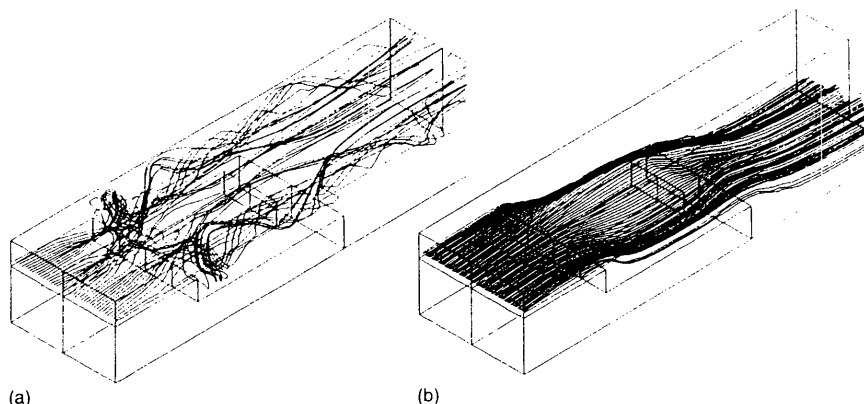
### Bibliography

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Gökoğlu, S.A.; Kuczmarski, M.; Tsui, P.; and Chait, A.: Convection and Chemistry Effects in CVD—A 3D Analysis for Silicon Deposition. Journal de Physique, Coll. C5, Suppl. 5, Tome 50, May 1989.

**Lewis contacts: Dr. Arnon Chait,  
(216) 433-3558; and Thomas K. Glasgow,  
(216) 433-5013**

**Headquarters program office: OSSA**



*Particle trajectories in chemical vapor deposition reactor:  
(a) normal gravity, (b) zero gravity*

## High-Burst-Rate Link Evaluation Terminal

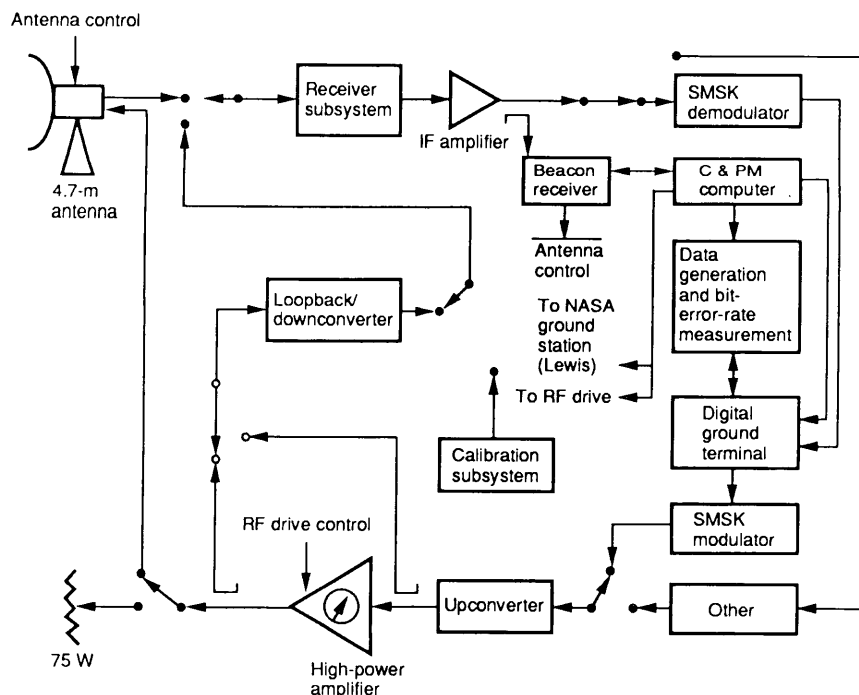
In support of the Advanced Communications Technology Satellite Project, NASA Lewis is developing the high-burst-rate link evaluation terminal. This versatile and adaptable experimental test facility will support various ACTS technology experiments such as the characterization of the multibeam communications package on the satellite and adaptive uplink and downlink radiofrequency power augmentation.

The terminal will operate at burst rates of 110 and 220 Mbps. Data rates are discretely variable from 1.25 to 200 Mbps. The digital subsystem has been designed and built at Lewis. Uplink power will be provided by a 30-GHz traveling-wave-tube amplifier that delivers 60 W of saturated radiofrequency power. The receiver subsystem will use a low-

noise receiver built by Harris Corporation for the ACTS Proof-of-Concept Program. Also utilized from that program will be a 4.7-m-diameter antenna built by Scientific Atlanta. An upconverter subsystem is being built at Lewis, as are the loopback and calibration subsystems. The loopback subsystem permits an end-to-end check of the terminal without open-loop operation. The calibration subsystem provides reference signals for calibrating the beacon receiver.

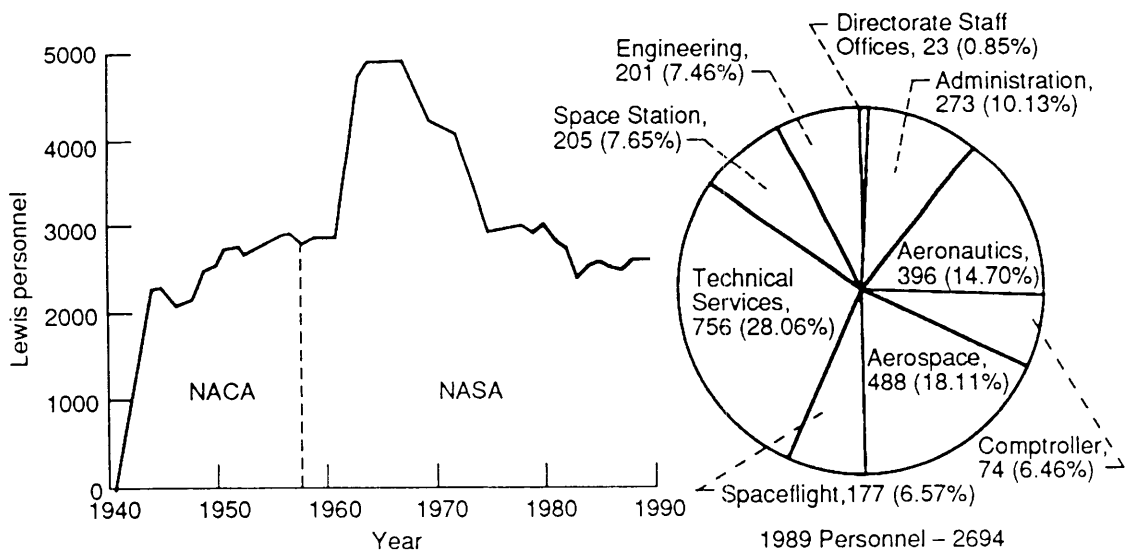
The terminal design is essentially complete. Subsystem components have been received and are undergoing acceptance tests. Subsystem integration has started. The project continues on schedule, within budget, and meeting technical objectives.

Lewis contact: Gerald J. Chomos,  
(216) 433-3485  
Headquarters program office: OSSA

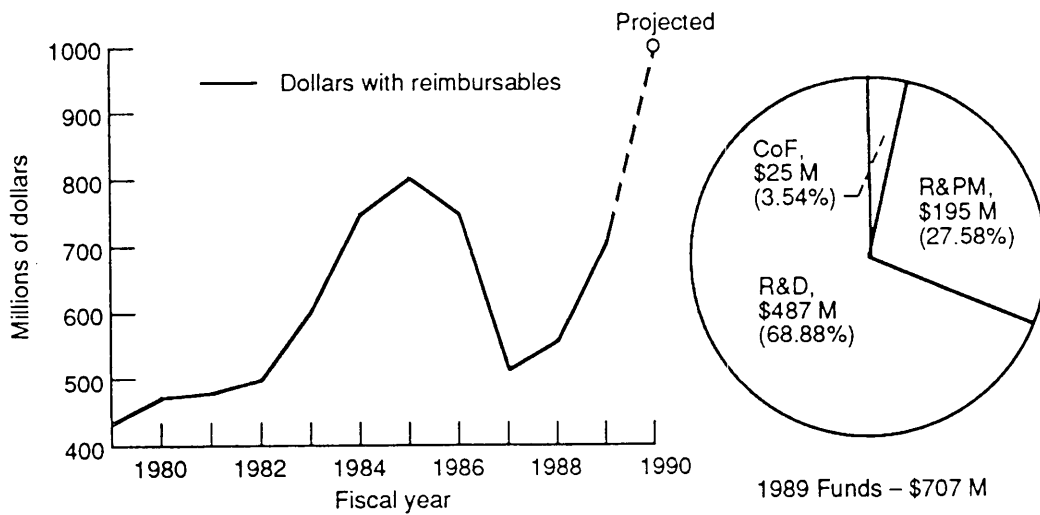


High-burst-rate link evaluation terminal

# PERSONNEL



# FUNDING



# Resources

## Strategic Objectives

- To strengthen the Center as a model of modern management.
- To effectively manage our financial resources.
- To increase financial resources for the institution and programs.
- To promote continuous improvements in quality and productivity.
- To increase the professional skill levels and stature of our staff.
- To provide the state-of-the-art computational equipment and software to meet growing needs in all facets of our work, including scientific computing, data acquisition and analysis, information systems, and communications, and thereby transform the Center into a model of excellence in these fields.
- To extend our staff through appropriate use of support service contractors.

# Programs

## Lewis Wins Quality Improvement Prototype Award

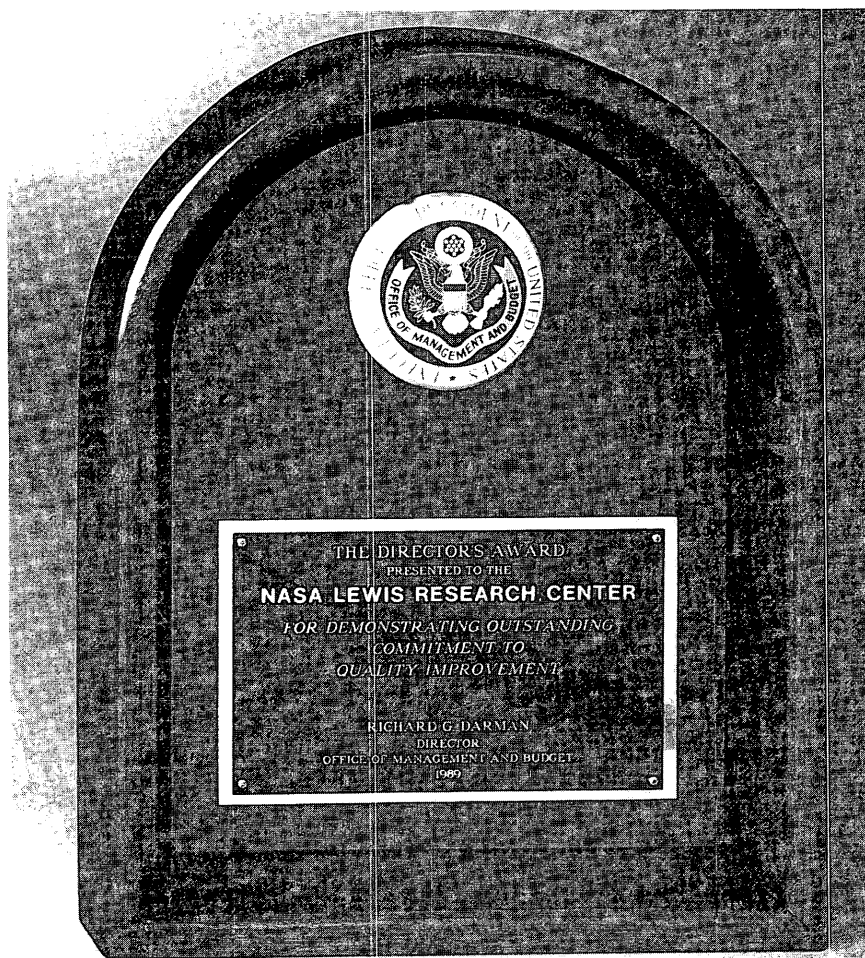
The Office of Management and Budget (OMB) selected NASA Lewis as a winner of the 1989 Quality Improvement Prototype Award. The award recognizes Federal Government achievements in the President's Productivity Improvement Program.

Lewis was one of only six Federal organizations to win this distinction and is the first research and development facility so honored. In announcing the selection, OMB Director Joseph Wright stated that "a prototype organization demonstrates an extraordinary commitment to quality improvement, focuses attention on satisfying its customers, and establishes high standards of quality, timeliness, and efficiency. This kind of organization also serves as a model for the rest of Government—showing how a commitment to quality leads to better and more efficient services and products for its customers."

Lewis was recognized for implementing a quality improvement process that focuses on team involvement and customer satisfaction as central priorities, leading to improved quality and efficiency in research and technological development. Specific factors mentioned included increases in technical publications; receipt of the 1987 Collier Trophy, an Emmy, and several R&D 100 awards; significant reductions in processing time for publications; dramatic increases in the number of employee suggestions; Awareness recognition and promotion programs; and many others.

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(216) 433-2914  
Headquarters program office: OSRM&QA

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*Quality Improvement Prototype Award*



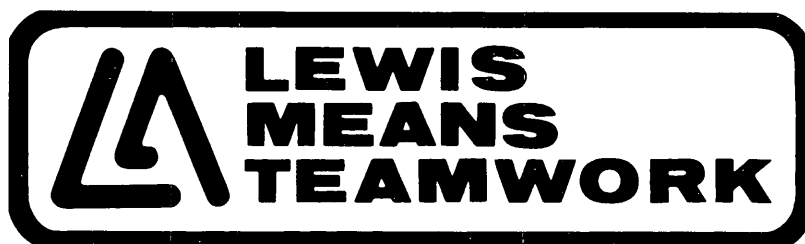
## Awareness

The NASA Lewis Awareness Program creates, develops, and leads internal programs that strengthen team pride, build employee commitment, and enhance communications. In 1989 the program resulted in 1784 civil service and contractor employees being honored for accomplishments through team recognitions and team promotions. Another 1810 employees were recognized for their contributions through special functions and "thank you" ceremonies. Approximately 6900 invitations were sent to employees for various communications activities, such as Issues and Answers (where the Center Director answers anonymous questions from employees), directorate messages, communication follow-ups, and "Let's Talk" programs covering specific topics at the Center.

Awareness is a Center Director program staffed by a program manager, a secretary, and more than 60 volunteers from around the Center. Costs incurred by program activities are paid for through nonappropriated funds, at no additional cost to the taxpayer.

The Awareness Program enhances communications between Center staff and senior management, builds employee dedication and pride in working together, promotes excellence, and encourages continued improvement. It further demonstrates top management support and concern for employee participation, teamwork, and outstanding performance.

The Awareness commitment to the future is "excellence by example based on leadership with cooperation". All senior managers participate actively in Awareness communications and recognition programs.



Lewis contact: Joyce E. Bergstrom,  
(216) 433-5658

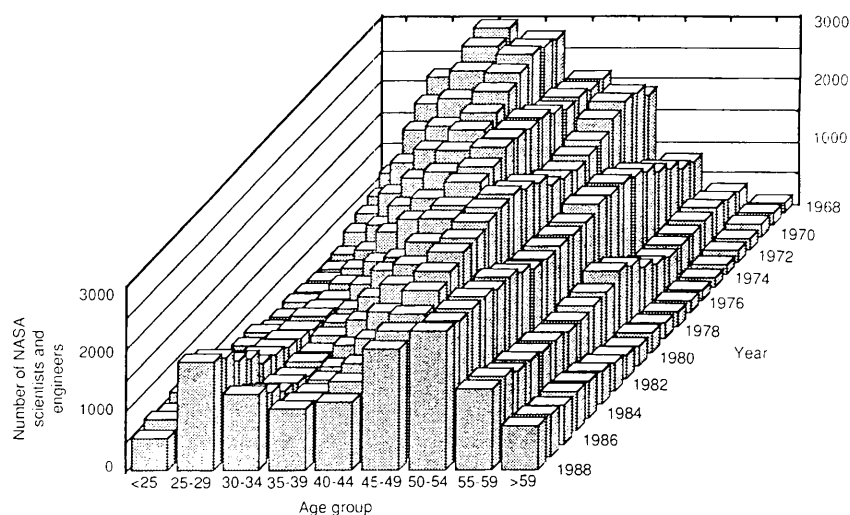
## Age Distribution Among NASA Scientists and Engineers

The loss of technical and managerial experience through attrition in the work force is a growing concern throughout NASA and the aerospace industry. A bimodal age distribution among scientists and engineers exacerbates the situation within NASA. It may preclude the smooth transition of managerial and technical responsibility as experienced s&E's are succeeded by a relatively few mid-level s&E's and inexperienced junior s&E's. This situation presents both challenges and opportunities to NASA managers.

Early in the U.S. civilian space program, after NASA was formed in 1958, many s&E's were hired directly from the collegiate ranks to supplement those s&E's who made the transition from the former NACA and s&E's reassigned from military programs. These s&E's acquired invaluable experience as they matured along with NASA through the Mercury, Gemini, and Apollo programs. However, forces external to NASA, such as congressional and administration priorities and corresponding budget constraints, resulted in a reduction in the size of the NASA civil service work force beginning in the late 1960's and extending throughout much of the 1970's. Authorization of major new programs, such as the space shuttle and the space station, and an influx of new hires since the early 1980's has revitalized the Agency. Nonetheless, as a result of the historical sequence of events that shaped the Agency work force, we are faced with the prospect of problems and opportunities resulting from a bimodal age distribution.

Recommendations for precluding potential problems and taking advantage of opportunities include hiring experienced s&E's, increasing awareness, supporting employee development programs, developing technical mentor programs, establishing positions for deputy managers and chief engineers/scientists, requiring documentation of work, and using contractors and consultants as appropriate.

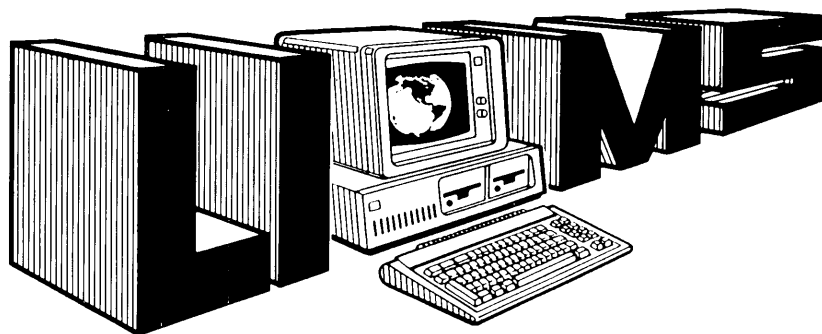
Lewis contact: Michael L. Ciancone,  
(216) 433-5387  
Headquarters program office: OM



Age distribution among NASA scientists and engineers

## Lewis Information Management System

NASA Lewis is implementing an information management system (LIMS) that will serve as a unified "window to the computing world." Lewis has been providing centralized computing services from several different mainframe systems and operating systems. LIMS can be thought of as a public utility that provides several services to the desk of the user: access to all of those mainframes, personal computing services, and electronic office support. Networking is provided by a series of local area networks, one in each of the 24 major office buildings at the Center, all bridged together through an interbuilding broadband network. Primary services are provided by a centrally located server system. These integrated services include electronic mail, word processing, time management, a spreadsheet, a data base, a statistical analysis package, graphics, and project management. On the desk of the user is a personal computer. This PC contains the basic communications and terminal emulations products and the same word-processing package that is provided centrally. Since users do have the capability and option to run their personal computers as stand-alones, they may load any third-party applications packages that they wish. The project, which began on May 1, 1987, also provides all support services including training, operations, maintenance, and a central help desk. Currently, a total of 1500 users are on the network and using the system. A grand total of 3000 civil servants and resident support contractor personnel will be served by the system when LIMS is completely implemented.



## LEWIS's Window to the World of Computing

To keep the LIMS solution from growing stagnant and dated, the contract has a unique clause in it for technology assessment. This mandates that new hardware and software be studied, and if feasible (and at the discretion of the Government), introduced into LIMS. Some of the technology being studied includes optical character readers and graphics scanners, print/file servers, the MS-Windows platform, and fiber optic routers. Additionally, Apple Macintosh II computers are being added to the traditional MS-DOS PC line of LIMS workstations. Also

under study for addition to LIMS are true scientific and engineering workstations. These 10+ MIPS workstations will run UNIX and TCP/IP and be fully configured for the scientist and engineer. This will provide Lewis scientists and engineers with enough computing power on their desks to do their research, *plus* provide for them the integration and service offered by LIMS.

**Lewis contact:** Ernest Roberts, Jr.,  
(216) 433-5183

# Organizations

## Office of the Comptroller

The Comptroller's Office is responsible for managing all aspects of resource planning, budgeting, allocation, expenditure, tracking, and reporting. The process begins with preparation, review, and Center approval of a long-range strategic plan. Next, shorter term, more specific budgets for the various sources of funding are prepared, reviewed, and approved. These Center-approved budgets are then submitted to, and defended before, the various NASA Headquarters program offices. When the budgets are ultimately approved, funds are transferred to the Center, and the Comptroller's Office assures that they are properly allocated within the Center and to approved efforts. The funds must then be placed on contract consistent with legislation and regulations. The last function is tracking all financial activity and reporting its status to Center management in special reviews and to the Center, Headquarters, and the Federal Government in the formal accounting system.

Lewis contact: Robert E. Fails,  
(216) 433-2977

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## Test Installations Division

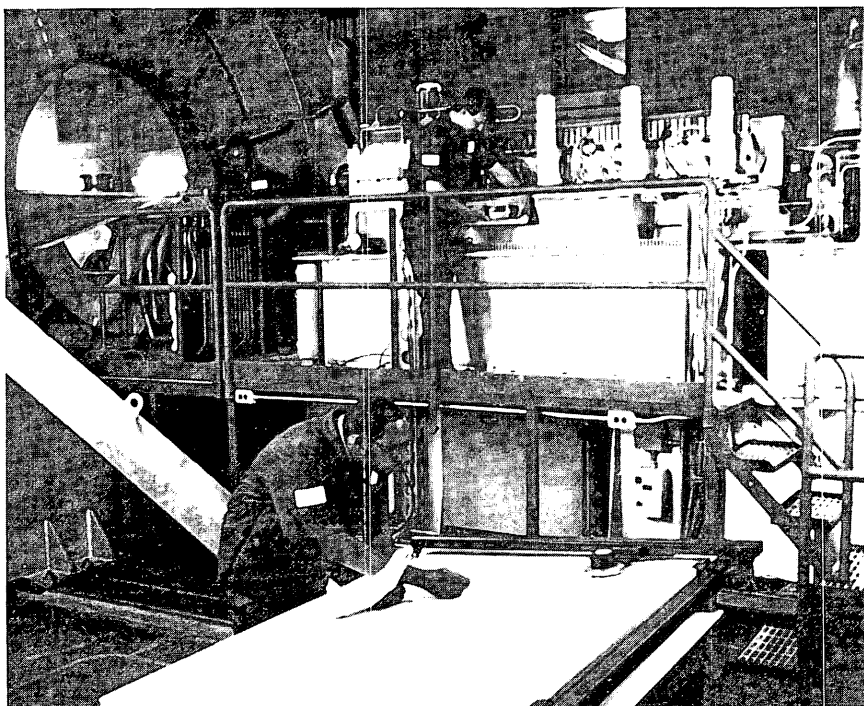
The Test Installations Division provides mechanical, electrical, and electronic technical support to fabricate, install, maintain, modify, repair, and operate all the research test models, rigs, facilities, and laboratories at Lewis. In addition, the Division is responsible for selected maintenance, repair, and upgrade of the shops, the shop equipment, and the buildings housing these resources. The Division is staffed by 400 research laboratory mechanics, electronic equipment mechanics, electricians, and supervisors.

Journeyman skills are developed through intern, co-op, and apprentice training programs. Special skills developed within the three major trades include optics, materials, microwave, wind tunnel, microelectronics, and aircraft/jet engine specialties. Division personnel meet the schedules and priorities of their research customers by getting involved at the inception of research programs and providing the technical expertise needed for project planning.

Lewis contact: Joseph H. Brown,  
(216) 433-3005

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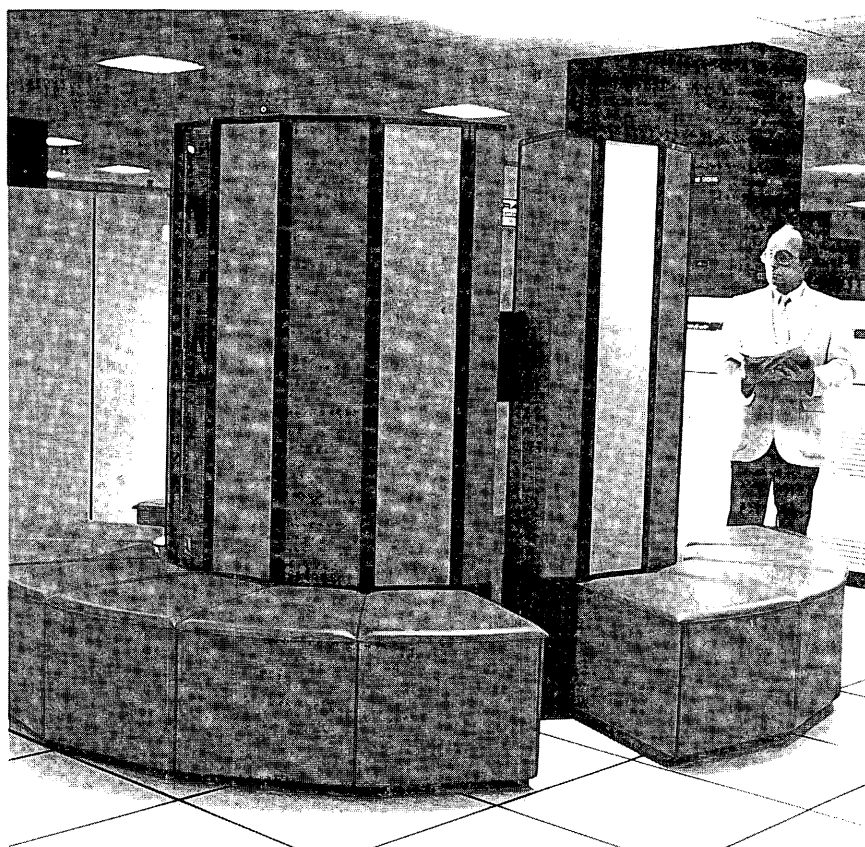
*Working on the buildup of the Large Low-Speed Centrifugal Compressor Facility*

## Computer Services Division

The Computer Services Division plans, develops, maintains, and operates a centralized computation facility used for acquiring and reducing scientific data, solving engineering problems, and performing other mathematical calculations. These activities support NASA Lewis efforts in research and development, data handling, and report processing, as well as the administrative and operational functions of the Center.

Within the Division are many different areas of activity. Work in computer systems and software is directed at large-scale digital computer systems used in support of scientific, engineering, and administrative users. Real-time application programs are developed for experimental investigations in fields such as aerodynamics, thermodynamics, structural mechanics, combustion, heat transfer, and fluid mechanics. And large applications programs, such as management information systems and computer-aided graphics systems, are developed to support *all* users of the Lewis computing complex, from office worker to research scientist.

The Division also develops computer hardware and system software for the minicomputers dedicated to the control of experimental tests and the automatic acquisition, display, and recording of data. Another challenging area is the design and implementation of new and dependable telecommunications and networking systems, for both internal and external communications. These include high-speed computer-to-computer links, as well as data acquisition, video, and remote interactive graphics display telecommunications.



*Cray X/MP*

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Besides its work in hardware and software, the Division also supports the research community by providing mathematical consultation and programming services and furnishes a myriad of administrative functions ranging from payroll to automated travel planning. As Lewis' dependence on technology and computers increases, so does its dependence on the Computer Services Division to provide those computers and the expertise required to maximize their usefulness.

Lewis contact: Dr. William F. Ford,  
(216) 433-5171

## Office of Mission Safety and Assurance

The Office of Mission Safety and Assurance is charged with the responsibility to assure that project and facility safety and reliability are commensurate with the human involvement and physical and scientific value of the project or facility. This is achieved by applying such tools as risk management, safety engineering, reliability engineering, and quality assurance engineering. The Office also supports projects involving electrical, electronic, and electromagnetic parts and materials and processes.

**Space experiments projects.**—Our support of these projects is based on assuring that the experiment will be safely transported into space and function safely while in space. Since space experiments projects will be carried aboard the space shuttle, a manned system, parts, materials, and processes must be carefully selected; appropriate ground tests and inspections must be performed to verify the efficacy of design and manufacture; and appropriate procedures must be followed to mitigate hazards. The Office has used its expertise to achieve this goal for such Lewis space experiments as the Advanced Communications Technology Satellite, the surface-tension-driven convection experiment, isothermal dendrite growth experiments, and the space acceleration measurement system. The specific support provided these space experiments includes preparation for the payload safety reviews; reliability analysis; establishment of quality standards for experiments that are being fabricated in house; and certification of technicians to perform critical manufacturing and inspection processes.

**Launch vehicle projects.**—The major thrust over the last year for the Office in its support of launch vehicle projects has been to develop a meaningful role in the Agency's new policy of procuring these vehicles commercially. Our Office has developed with General Dynamics, from whom we are commercially procuring Atlas-Centaur launch vehicles for the Geostationary Operational Environmental Satellites, a system effectiveness plan that can be used as a baseline against which to measure contractor performance. A similar plan has been developed with Martin Marietta for use in the anticipated commercial procurement of a Titan III launch vehicle for the Mars Observer Mission.

**Space Station Freedom.**—Because NASA is requiring that Space Station *Freedom* remain operational for at least 30 years, the design, fabrication, and testing of its hardware must meet new, innovative, and more stringent requirements. During the last year the Office has been developing such requirements for safety, reliability, maintainability, quality assurance, parts, materials, and processes. With these requirements essentially complete, work on Space Station *Freedom* can begin with the assurance that it will be built to serve the Nation safely and efficiently over its intended lifetime.

**Lewis contact:** Wilson F. Ford,  
(216) 433-2350  
**Headquarters program office:** OSRM&QA

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## Office of Human Resources Development

The Office of Human Resources Development (OHRD) was created in fiscal 1989 to provide greater emphasis and support to the development of the Center's work force. Through the Training and Development Branch, the OHRD provides all employees with the opportunity to increase their technical knowledge and work-related skills. The Awareness Office, in OHRD, plans and coordinates the Center's internal information and team recognition efforts.

training courses to increase their ability to manage the Center's highly technical work force. In addition to supporting its ongoing efforts, the OHRD also introduced a new career development process that will be provided to all employees in the coming year.

**Lewis contact: Richard D. Clapper,**  
**(216) 433-2890**

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In fiscal 1989, 83 percent of the Center's 2700 civil service employees received job-related training. Training experiences included both on-site and off-site academic and nonacademic training. Over 100 technical courses were sponsored at Lewis as were graduate-level academic programs in electrical engineering, mechanical engineering, civil engineering, industrial engineering, computer information science, and business. Technical training addressed the topics of hypersonic flows, radiation and heat transfer, applied thermodynamics, NASTRAN modeling, fiber optics, digital communications, Ada programming, and many others. A specially designed in-house course was presented by Lewis experts in wind tunnel operations. Business-related skills addressed included contract administration, recruiting, travel administration, network and minicomputer security, accounting, and human relations in business.

Training was also provided to help employees and managers develop the teamwork and communications skills so critical to job completion and satisfaction. Most of the Center's managers (89 percent) participated in

## Fabrication Support Division

The Fabrication Support Division manufactures hardware required by engineering, research, and service organizations at the Center. Division personnel provide metallurgical consultation and material selection services to research, engineering, and service divisions. The Division also supports and controls the application of equipment and technologies required to fabricate, instrument, and inspect hardware manufactured internally or procured through outside sources.

On May 5, 1989, the Fabrication Support Division awarded a five-year \$11 million task draw contract to West Tool to augment the outside

fabrication capability. Work on a contract with the University of Arizona in support of the full-scale accurate antenna was also completed this year. This activity involved critical machining of the 8-ft parabolic mirror within a 1/2-mil tolerance band. The first Sitka spruce replacement blade for the Icing Research Tunnel was completed, inspected, and approved; delivery of the remaining thirteen 14-ft blades is scheduled for December 1989.

Lewis contact: Carl P. Wendt,  
(216) 433-2214

## Facilities Engineering Division

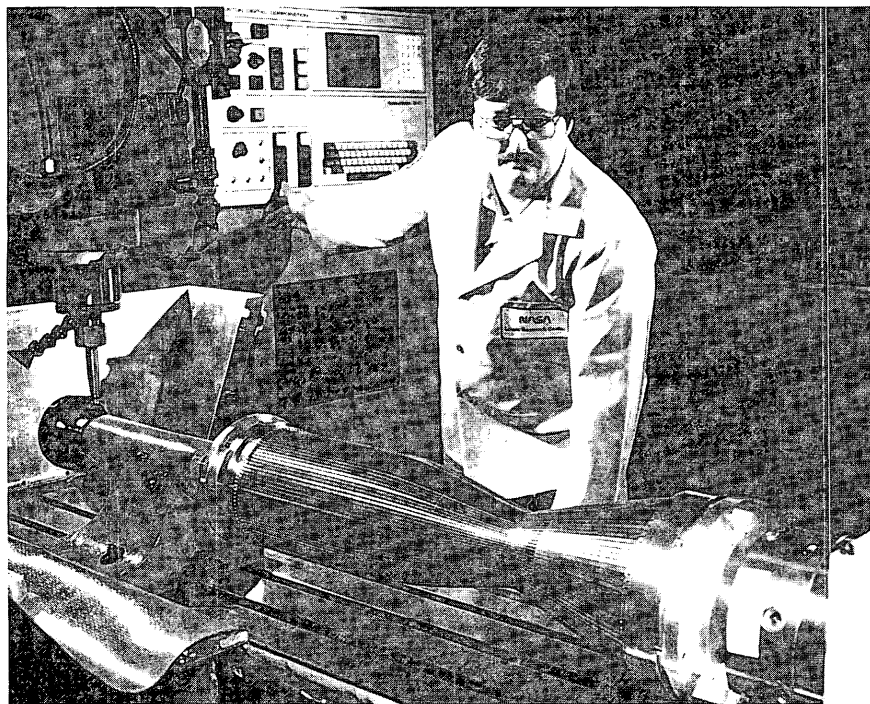
The Facilities Engineering Division provides a wide range of engineering services for the Center's research and institutional facilities in support of research activities. The Division is staffed by approximately 100 engineers and engineering technicians, who are supported by an engineering contractor employing about 50 engineers. Related construction activities are performed through individual contractor-construction projects managed by Division personnel.

Division personnel serve as engineering authorities for the construction of research and institutional facilities and systems. They establish and maintain design and construction standards, drawings, and records for facility design, analysis, costs and schedules, construction inspection, and construction contracting.

The Facilities Engineering Division is the Center's primary interface with NASA Headquarters for both the advocacy and technical content of facility projects. Division engineers provide construction-of-facilities planning, conceptual designs, preliminary engineering reports, final designs, and inspection. The Division also manages locally funded facility projects, provides engineering and architectural services for the operation and maintenance of the Center, and provides Lewis with consultant services on facility matters.

In 1989 the Facilities Engineering Division supported research for rehabilitation projects involving the Fan and Compressor Facility, the Materials and Structures Annex, the High Temperature Composites Laboratory, the 8- by 6-Foot

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*Contour machining*



### Logistics Management Division

Supersonic Wind Tunnel, the Propulsion Systems Laboratory, the Rocket Engine Test Facility, and the Cryogenic Components Laboratory.

Lewis contact: Charles E. Yesberger,  
(216) 433-2916

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The Equipment Management Branch of the Logistics Management Division directs all technical, operational, and administrative activities incident to equipment management, industrial property management, metrological and instrumentation equipment pooling and calibration support services, and fluid flowmeter and gas analysis systems at Lewis.

The Branch administers Lewis support of NASA's Equipment Management System (NEMS), Industrial Property Management Information System (NIPMIS), and Metrology Information System (NMIS). It provides administrative support for the retention and storage of inactive property, inbound and outbound loans of Government

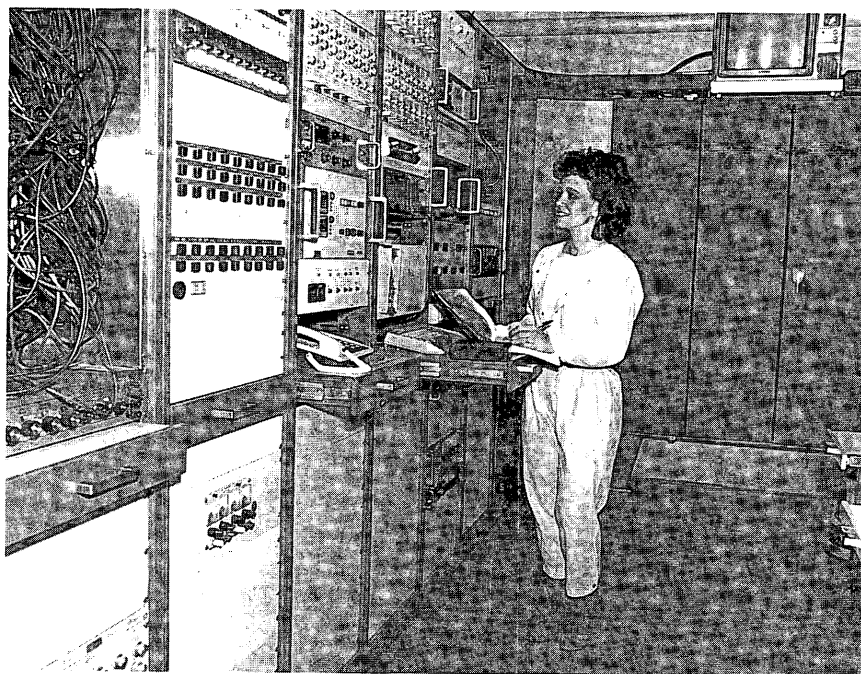
property, cannibalization of equipment, and survey reports for lost, damaged, or destroyed property.

The Branch also provides administrative and technical support for the Lewis CLASS contract in the areas of equipment management; NEMS, NIPMIS, and NMIS support; instrument pool maintenance; instrument acceptance inspection, testing, repair, and calibration services; U.S. Air Force interservice metrology and calibration; fluid flowmeter and exhaust gas analysis equipment maintenance; and administrative office machine repair.

Lewis contact: James M. Vrtis,  
(216) 433-3091

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*Property custodian checking Center's capitalized equipment*

## Technical Information Services Division

### Library Branch

The NASA Lewis library supports the information needs of the Center through consultation services; the Library's collection of books, journals, research reports, and specifications; reference services based on NASA's computerized bibliographic system, RECON, as well as Federal and commercial on-line data bases; current awareness services through Selected Current Aerospace Notices (SCAN) and Update (a customized personalized stored search); and interlibrary loan services. The Library is also responsible for the records management program at the Center.

In 1989 a secure terminal able to access the Defense Research and Development, Test, and Evaluation On-Line System was put into operation. This service is available to all civil service employees with the appropriate security clearance. Immediate response time to meet our patrons' needs has been the greatest advantage of this new on-line system. Previous access to these files was by the U.S. mail.

Lewis contact: Leona T. Jarabek  
(216) 433-5767

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### Editorial Branch

*"By his own definition, a copy editor takes the rough clay of an author's labors, smooths out phrases here and punctuation there, reworks spelling and grammar and shapes the mess into a certain coherence."*

*"By the author's definition, a copy editor is a grouch who sees his mission in life as taking dazzling prose and removing the dazzle, plucking out the pearls like an oyster shucker."*

—Anonymous

However you look at it, the Editorial Branch provides this service to NASA Lewis scientists, engineers, and administrators. Editors work on Special Publications, which present subjects of substantial public interest, such as the recent "Advanced Turboprop Project"; and Reference Publications, which contain complete or comprehensive results in a given topic or discipline, such as this year's RP's on the theory of gearing, fastener design, structural properties of laminated wood, exhaust nozzles for supersonic aircraft, and the foundations of measurement and instrumentation. And then there are Technical Papers, the results of completed research; Technical Memorandums, which contain information of immediate interest and are edited only on request; conference publications, for which we edit Lewis-authored papers and coordinate the rest; Contractor Reports; brochures, such as this "Annual Report"; penny brochures; and Lewis Management Instructions. Recently, we have begun to edit abstract-and-figure preprints for conferences, such as LST '88 and this year's HITEMP.

All these edited documents then receive the services of our word

processors and typesetters. Many technical memorandums, presentations, and journal articles are not edited but handled directly by the word processors.

In fiscal 1989, a total of 595 documents were processed by the Editorial Branch.

Lewis contact: Sylvia C. Taylor,  
(216) 433-5791

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### *Graphics and Exhibits Branch*

The Graphics and Exhibits Branch provides full graphics, exhibits, and forms development services to the Center staff. Graphics for technical research publications and presentations are created on computerized workstations or with traditional artist's tools and techniques. Artists work closely with requesters on informational program brochures, presentation shows, and videos—extending awareness of Center activities throughout the Agency and the worldwide technical community.

Programs such as ACTS and COLD-SAT that require special support receive the dedicated services of a suitable talent, who creates all the relevant art necessary for presentations, publications, and displays.

Graphics fully supports Lewis' participation in scientific and technical conferences. In recent years Graphics has provided a new service to the Center. In a concerted effort with the Editorial Branch and the Photographic and Printing Branch, we provide figure-abstract preprints of conference proceedings, such as LST '88 and this year's HITEMP, on request.

Full-scale exhibits are designed and fabricated for use in technical society conferences and informational community outreach programs. The forms needed for efficient Center operation are electronically created and managed by the Branch's forms manager. All photomaterial required by the various technical and research societies for their publications as well as for internal printing needs is prepared by our composers.

Lewis contact: Dennis Dubyk,  
(216) 433-5805

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*Artists at work on computerized workstations*

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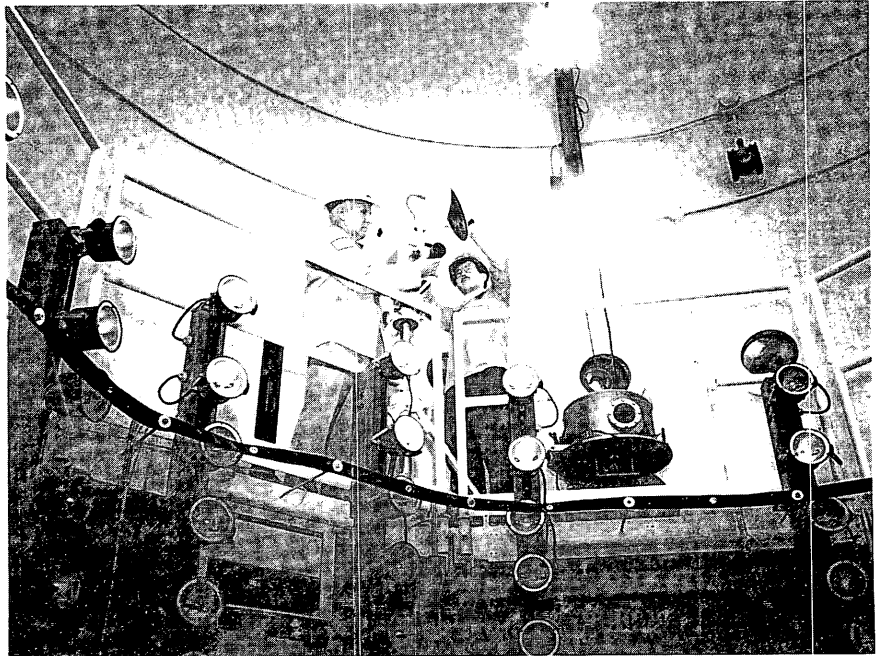
***Photographic and Printing Branch***

***Photo Lab.***—The photographic staff of the Photographic and Printing Branch provides complete classified and unclassified imaging support for Center research requirements as well as support for NASA Headquarters, other NASA centers, and other Government agencies. Imaging services include high-speed motion picture and television production; photographic and video instrumentation; space science imaging systems; consultation and development of imaging systems for research data acquisition; still photography; film and print processing; and graphic arts camera operation. Additionally, technical film and video documentaries are produced for research report supplements and for presentation at technical society meetings.

The Branch's photographic services staff uses such new imaging and photofinishing technologies as optical disk systems, video graphics/animation, and nonsilver imaging systems to support the research staff. It also provides an imaging library service to Government researchers, industry, and universities, storing and maintaining reference files of film, tape, and negative originals.

The Branch also administers on-site photographic support service contractors and off-site processing support service contracts.

These photographic services are required to maintain support and mission imaging requirements for a growing population of scientists and engineers. The demand for service increases each year with the growth of the research population. Individual jobs handled primarily for research projects have nearly doubled in the last five years.



*Setting up a high-speed motion picture camera in Zero Gravity Facility*

Lewis contact: William R. Richardson,  
(216) 433-5982

### Support Service Contractors

**Print Shop.**—The printing and reproduction staff of the Photographic and Printing Branch provides complete classified and unclassified printing and reproduction services for the Center's research and development requirements and support for other Government agencies. These services include printing, cutting, folding, collating, stitching, and drilling in the reproduction of research reports, technical articles, brochures, illustrations, and a variety of other publications. We also provide technical advice on printing equipment, services, and processes.

We assure conformance with NASA and Lewis management instructions and Joint Committee on Printing and Government Printing Office regulations.

Copying practices, procedures, equipment, and supplies are managed to ensure effective and economical copying. We provide and monitor four copy centers and 123 copiers for the Center. These copiers produced 35.5 million photocopies in fiscal 1989.

The Print Shop staff is responsible for in-house printing (JCP approved) and in fiscal 1989 processed 6273 workorders and produced 14.7 million impressions. We also administer the on-site printing support service contractors and off-site printing support contract.

NASA Lewis augments its staff with approximately 1700 support service contractors (ssc's). Of the 1700 ssc's, about 500 directly support the research and development effort at Lewis and its Plum Brook Station. They carry out critical tasks and assignments that enable the Center to meet commitments in expanding programs in a timely fashion.

The ssc's manage programs, work directly with researchers, are part of project teams, run facilities, consult in areas of their expertise, write software, repair equipment, and provide editorial support. Presently, the ssc's are housed throughout the Center, but several contractors are having facilities built in the new industrial park located on land adjacent to Lewis. The first of these facilities was completed in the fall of 1989.

Lewis contact: Stephen M. Stefka,  
(216) 433-5990

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# Facilities

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## Defense Technical Information Center Terminal

Civil service employees can now be linked directly to the Defense Technical Information Center (DTIC) in Alexandria, Virginia, via a terminal located in a secure room in the NASA Lewis Library.

The terminal, which was dedicated and officially opened on April 10, 1989, allows a direct connection to the DTIC, which is the repository for all of the research reports produced under Government sponsorship, both classified and unclassified. Five major data bases can be accessed, including Defense Technical Reports, Work Unit Information Summary, Current File, New Accessions, and Independent Research & Development. The latter is of particular significance to Lewis because of its participation in Independent Research & Development evaluations, a responsibility that was the impetus behind this terminal.

Use of the terminal is restricted to civil service employees. Those assigned black badges can access unclassified topics, and those issued red badges can access both classified and unclassified topics. The terminal must be operated by one of the qualified civil service librarians.

The terminal is located in a secure room in the Library behind the reference desk. Entrance to the room is through a vault door. Other secure measures include no windows in the room, radiofrequency shielding, and a secure telephone line. Classified information is transmitted via cryptographic gear connected to the terminal. Authorized persons are encouraged to use the terminal.



*Dedication of DTIC terminal*

Lewis contact: Susanne F. Oberc,  
(216) 433-5766

### Alliant FX/80 Parallel Processor

Presently considered an experimental system, the Alliant FX/80 with its multiprocessor architecture and fast memory delivers high performance for computationally intensive scientific and engineering applications, primarily computational fluid dynamics and structural dynamics.

Alliant's intelligent FX/Fortran compiler detects the potential for vector and parallel processing in standard Fortran code and does much of the optimization automatically. Also, because Alliant users can monitor and control the optimization, they can gain insight into how to develop software that takes advantage of parallelism.

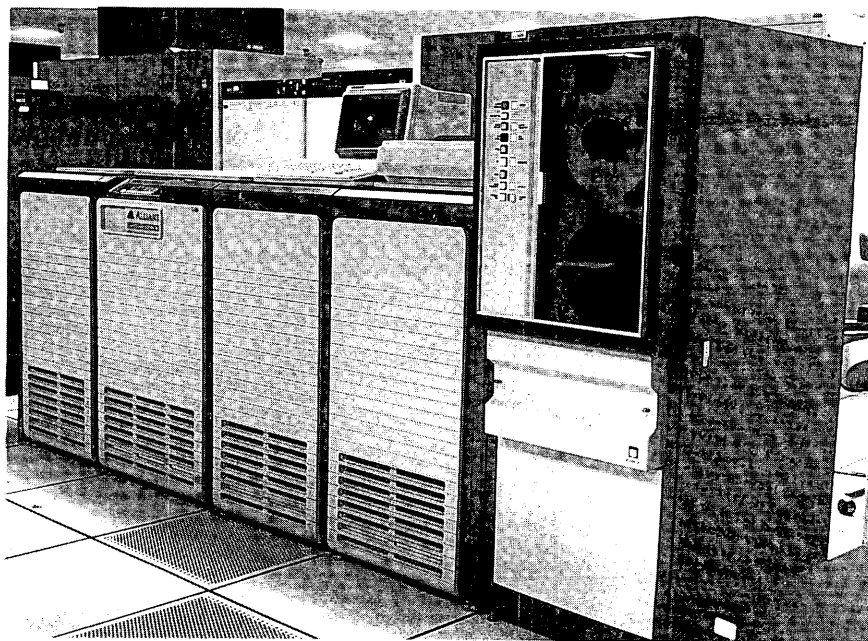
The Alliant's eight vector processors, called computational elements, can be used for multiprocessing to achieve faster system throughput, or they can be combined to work simultaneously on a single computationally intensive job. An additional 12 general-purpose processors handle editing and other interactive processing.

Researchers in several areas have used the Alliant to demonstrate how various codes can be adapted to parallel architectures. Alliant is used in both basic and applied computational fluid dynamics research. Time-dependent incompressible fluid dynamics algorithms are being researched and adapted to the Alliant's parallel architecture. Alliant is also being used to investigate the effect of parallel processing on computational structural mechanics. The machines are used as parallel resources in research involving the Engine Structures Computational Simulator (ESCS). In the future the Alliant will be used in combustor

research, in Stirling engine applications, and in research involving jets and crossflows for both combustors and VSTOL operations.

**Lewis contact: Dr. Steven M. Sidik,  
(216) 433-5187**

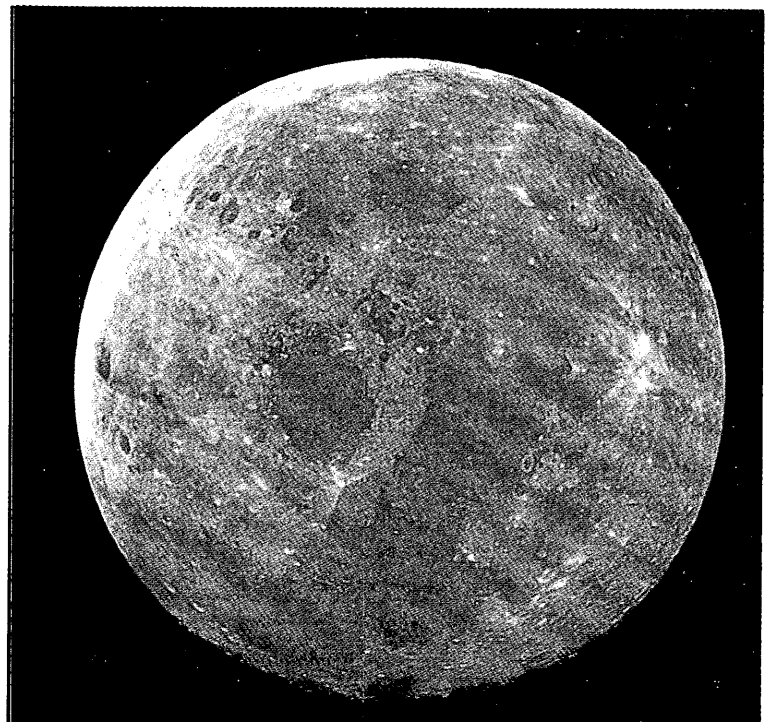
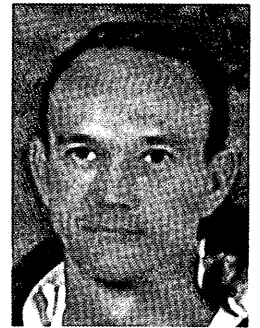
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*Alliant FX/80*







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National Aeronautics and  
Space Administration

**Lewis Research Center**  
Cleveland, Ohio 44135